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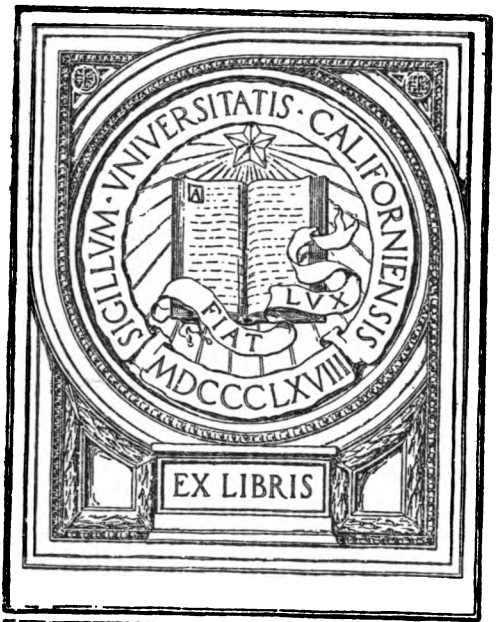

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UNITED STATES DEPARTMENT OF AGRICULTURE

BULLETIN No. 1091

Also Technical Bulletin No. 1 of the Agricultural Experiment Station
University of Arizona

Washington, D. C. PROFESSIONAL PAPER September 13, 1922

1926

LIFE HISTORY OF THE KANGAROO RAT

Dipodomys spectabilis spectabilis Merriam

BY

CHARLES T. VORHIES, Entomologist
Agricultural Experiment Station, University of Arizona; and

WALTER P. TAYLOR, Assistant Biologist
Bureau of Biological Survey, U. S. Department of Agriculture

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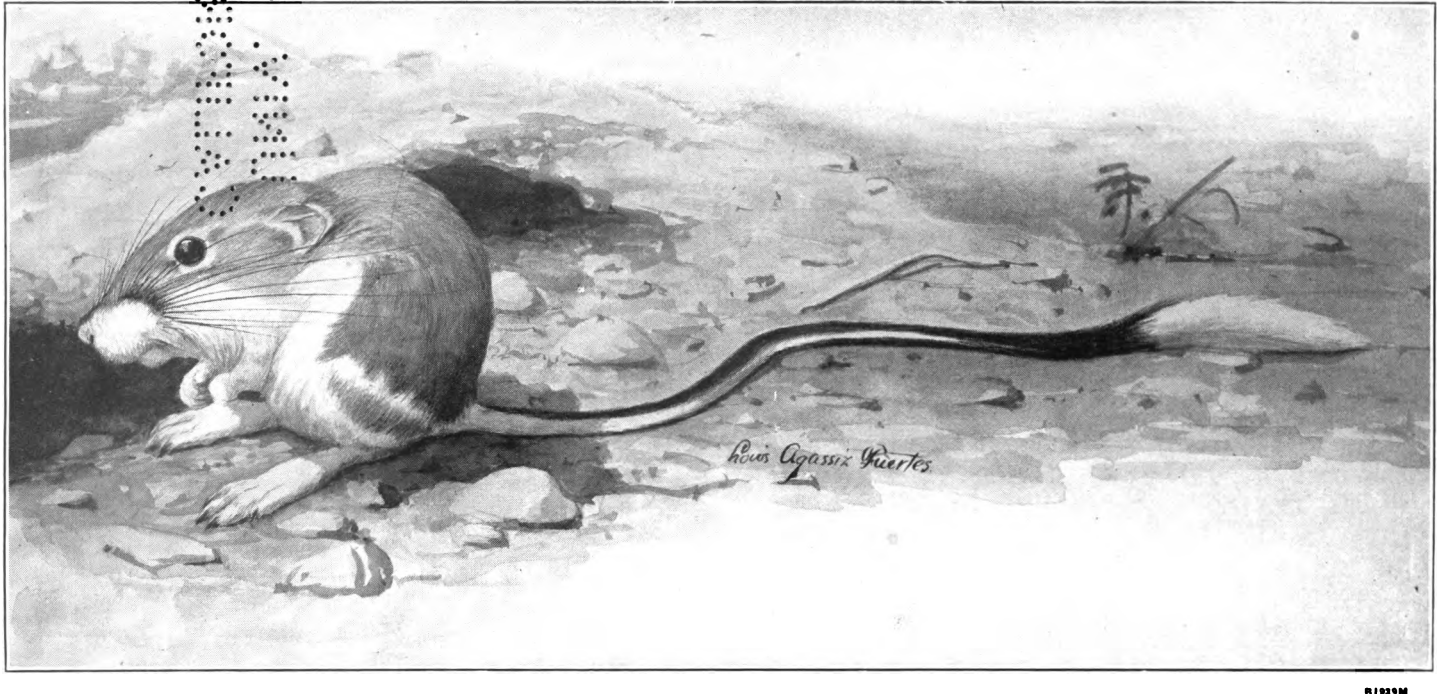

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BANNER-TAILED KANGAROO RAT (DIPODOMYS SPECTABILIS SPECTABILIS MERRIAM).

From *Dipodomys merriami* Mearns and subspecies, which occur over much of its range, this form is easily distinguished by its larger size and the conspicuous white brush on the tail.

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LIFE HISTORY OF THE KANGAROO RAT,

Dipodomys spectabilis spectabilis Merriam.

By CHARLES T. VORHIES, *Entomologist, Agricultural Experiment Station, University of Arizona;* and WALTER P. TAYLOR, *Assistant Biologist, Bureau of Biological Survey, U. S. Department of Agriculture.*

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IMPORTANCE OF RODENT GROUPS.

AS THE serious character of the depredations by harmful rodents is recognized, State, Federal, and private expenditures for their control increase year by year. These depredations include not only the attacks by introduced rats and mice on food materials stored in granaries, warehouses, commercial establishments, docks, and private houses, but also, particularly in the Western States, the ravages of several groups of native ground squirrels and other noxious rodents in grain and certain other field crops. Nor is this all, for it has

NOTE.—This bulletin, a joint contribution of the Bureau of Biological Survey and the Arizona Agricultural Experiment Station, contains a summary of the results of investigations of the relation of a subspecies of kangaroo rat to the carrying capacity of the open ranges, being one phase of a general study of the life histories of rodent groups as they affect agriculture, forestry, and grazing.

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been found that such rodents as prairie dogs, pocket gophers, marmots, ground squirrels, and rabbits take appreciable and serious toll of the forage on the open grazing range; in fact, that they reduce the carrying capacity of the range to such an extent that expenditures for control measures are amply justified. Current estimates place the loss of goods due to rats and mice in warehouses and stores throughout the United States at no less than $200,000,000 annually, and damage to the carrying capacity of the open range and to cultivated crops generally by native rodents in the Western States at $300,000,000 additional; added together, we have an impressive total from depredations of rodents.

The distribution and life habits of rodents and the general consideration of their relation to agriculture, forestry, and grazing, with special reference to the carrying capacity of stock ranges, is a subject that has received attention for many years from the Biological Survey of the United States Department of Agriculture. As a result of the investigations conducted much has been learned concerning the economic status of most of the more important groups, and the knowledge already gained forms the basis of the extensive rodent-control work already in progress, and in which many States are cooperating with the bureau. If the work is to be prosecuted intelligently and the fullest measure of success achieved, it is essential that the consideration largely of groups as a whole be supplemented by more exhaustive treatment of the life histories of individual species and of their place in the biological complex. The present report is based upon investigations, chiefly in Arizona, of the life history, habits, and economic status of the banner-tailed kangaroo rat, *Dipodomys spectabilis spectabilis* Merriam (Pl. I).

INVESTIGATIONAL METHODS.

Some 18 years ago (in 1903) a tract of land 49.2 square miles in area on the Coronado National Forest near the Santa Rita Mountains, Pima County, southern Arizona, was closed to grazing by arrangement between the Forest Service and the Agricultural Experiment Station of the University of Arizona. Since that time another small tract of nearly a section has been inclosed (Griffiths, 1910, 7 [1]). This total area of approximately 50 square miles is known as the United States Range Reserve, and is being devoted to a study of grazing conditions in this section and to working out the best methods of administering the range (Pl. II, Fig. 1).

[1] References in parentheses are to the Bibliography, p. 40 (the last figure being to the page of the publication). References to authorities where no citation of literature is appended relate for the most part to manuscript notes in the files of the Biological Survey or the University of Arizona Agricultural Experiment Station.

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For some years an intensive study of the forage and other vegetative conditions of this area has been made, the permanent vegetation quadrat, as proposed by Dr. F. E. Clements (1905, 161–175), being largely utilized. During the autumn of 1917 representatives of the Carnegie Institution and the Arizona Agricultural Experiment Station visited the Reserve and were impressed with the evidence of rodent damage to the grass cover. The most conspicuous appearance of damage was noted about the habitations of the banner-tailed kangaroo rat (*Dipodomys spectabilis spectabilis* Merriam), although it was observed also that jack rabbits of two species (*Lepus californicus eremicus* Allen and *L. alleni alleni* Mearns), which were very abundant in some portions of the reserve, were apparently affecting adversely the forage conditions in particular localities. Accordingly, the Biological Survey, the Agricultural Experiment Station of the University of Arizona, the Carnegie Institution of Washington, and the U. S. Forest Service have undertaken a study of the relation of the more important rodents to the forage crop of the Range Reserve in Arizona.

The present paper is a first step in this larger investigation.[2] In this work the authors have made no attempt to deal with the taxonomic side of the kangaroo rat problem. It is not unlikely that intensive studies will show that the form now known as *Dipodomys spectabilis spectabilis* is made up of a number of local variants, some of them perhaps worthy of recognition as additional subspecies. But it is felt that the conclusions here reached will be little, if at all, affected by such developments.

Color descriptions are based on Ridgway's Color Standards and Color Nomenclature published in 1912.

IDENTIFICATION.

There are only three groups of mammals in the Southwest having external cheek pouches. These are (*a*) the pocket gophers (Geomyidæ), which have strong fore feet, relatively weak hind feet, and short tail, as compared with weak fore feet, relatively strong hind feet, and long tail in the other two; (*b*) the pocket mice (*Perognathus*), which are considerably smaller than the kangaroo rats and

[2] In addition to assistance rendered by officials of the Biological Survey and the University of Arizona, which is hereby acknowledged, the authors are indebted to the following persons for helpful suggestions and assistance: G. S. Miller and J. W. Gidley, of the U. S. National Museum; Dr. Frederic E. Clements and Gorm Loftfield, of the Carnegie Institution; Morgan Hebard, of the Academy of Natural Sciences of Philadelphia; James T. Jardine and R. L. Hensel, both formerly connected with the U. S. Forest Service; and R. R. Hill, of the Forest Service. They are also indebted to William Nicholson, of Continental, Ariz., for many courtesies extended in connection with work on the Reserve.

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lack the conspicuous white hip stripe possessed by all the latter; and (*c*) the kangaroo rats (*Dipodomys*).

Dipodomys spectabilis spectabilis Merriam requires comparison with three other forms of kangaroo rats in the same general region, namely, *D. deserti* Stephens, of approximately the same size, and *D. merriami* Mearns and *D. ordii* Woodhouse, the last two of decidedly smaller size. The range of *deserti* lies principally to the

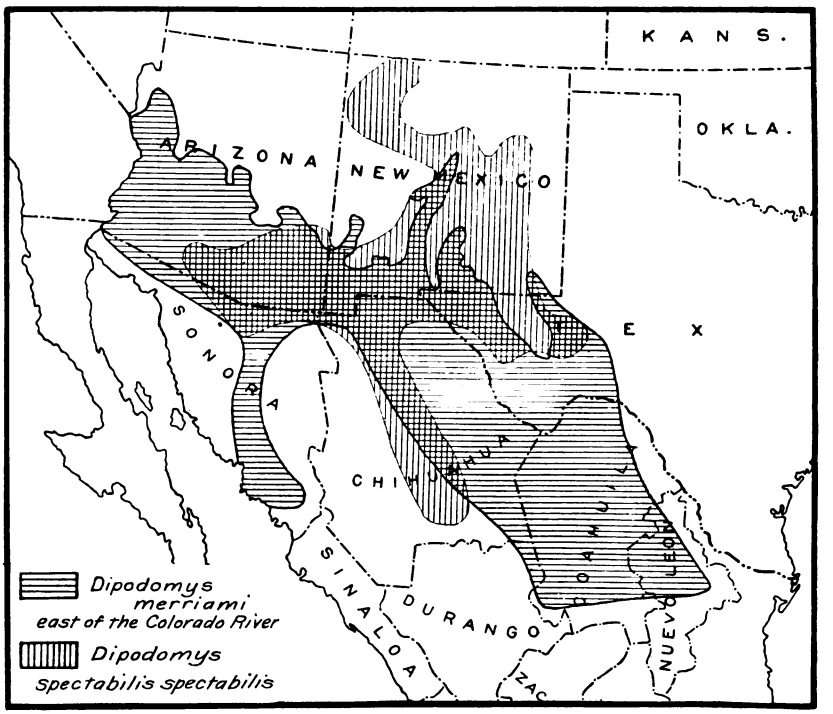

FIG. 1.—Range, east of the Colorado River, of *Dipodomys spectabilis spectabilis* compared with that of *Dipodomys merriami*. Cross hatching indicates area of overlapping of the two forms. The range of *Dipodomys deserti*, not shown on the map, is west of that of *spectabilis*, and so far as known the two do not overlap.

west of that of *spectabilis*, and the two do not, so far as known, overlap. On the other hand, *merriami* and *ordii*, and subspecies, occur over a large part of the range of *spectabilis*, living in very close proximity to its burrows; *merriami* is even suspected of pillaging the stores of *spectabilis*. The range of *merriami*, however, is much more extensive than that of *spectabilis* (Fig. 1), which argues against a definite ecological dependence or relationship. Separation of the four forms mentioned may be easily accomplished by the following key:

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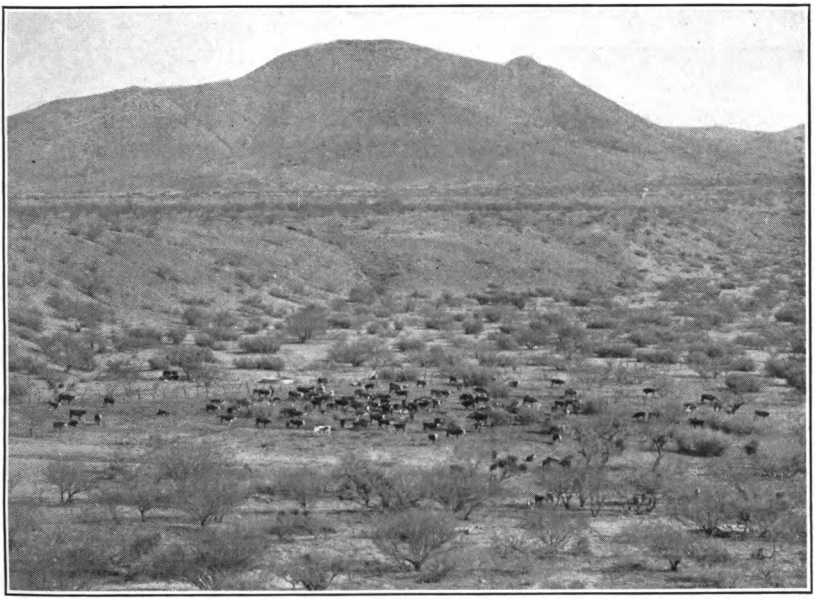

FIG. 1.—WINTER VIEW OF AREA INHABITED BY KANGAROO RATS.

A water-hole scene on the U. S. Range Reserve at the base of the Santa Rita Mountains, Ariz., where cooperative investigations are being conducted to ascertain the relation of rodents to forage. This is typical of a large section of country occupied by *Dipodomys spectabilis spectabilis* and *Dipodomys merriami*. The brush is mesquite (*Prosopis*), cat's-claw (*Acacia*), and paloverde (*Cercidium*).

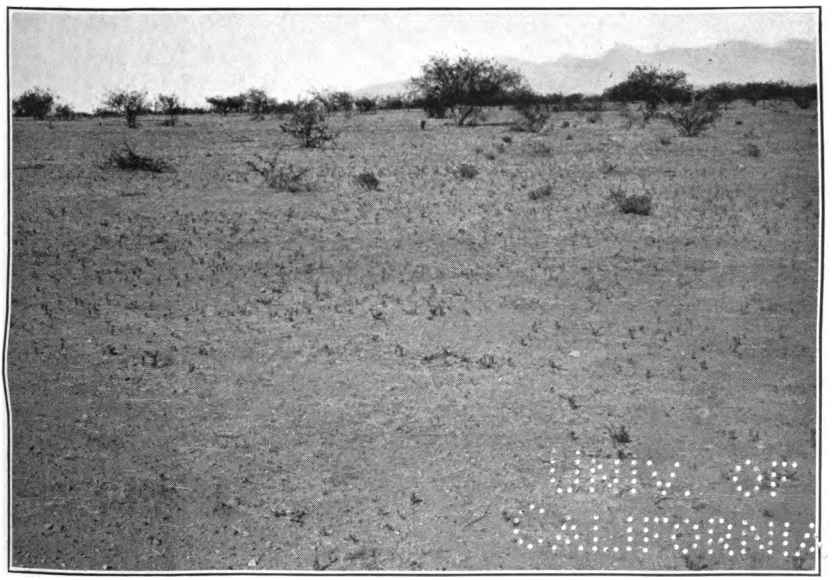

FIG. 2.—KANGAROO RAT COUNTRY FOLLOWING SUMMER DROUGHT.

An area of the U. S. Range Reserve in the autumn of 1918, showing the result of failure of summer rains. Such a condition is critical not only for the stockmen but also for kangaroo rats and other desert rodents, and results in competition between them as to which shall benefit by what the range has to offer.

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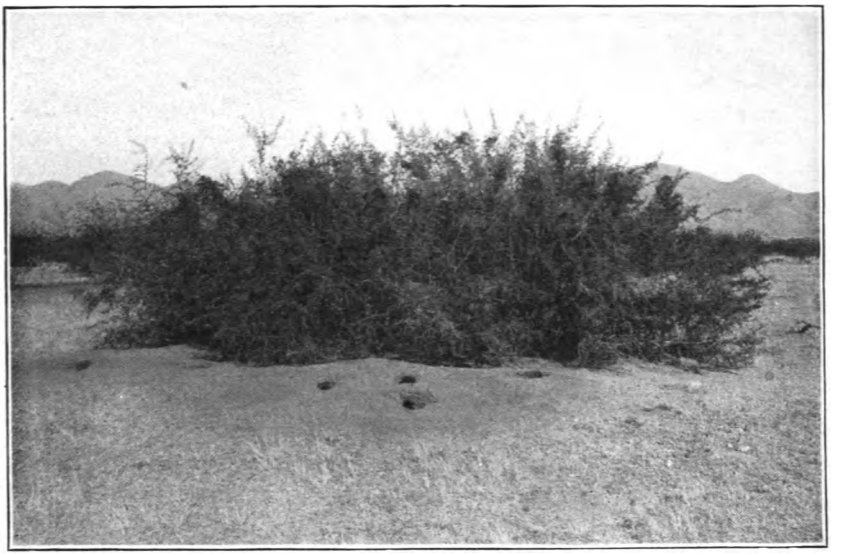

FIG. 1.—KANGAROO RAT MOUND (DIPODOMYS S. SPECTABILIS).

Typical *Dipodomys s. spectabilis* mound on the Range Reserve, under shelter of desert hackberry (*Celtis pallida*). Most dens on the reserve are located in the shelter of brush plants, the more important being mesquite (*Prosopis velutina*), cat's-claw (*Acacia* spp.), and the desert hackberry. (See also Pl. VIII Fig. 2.)

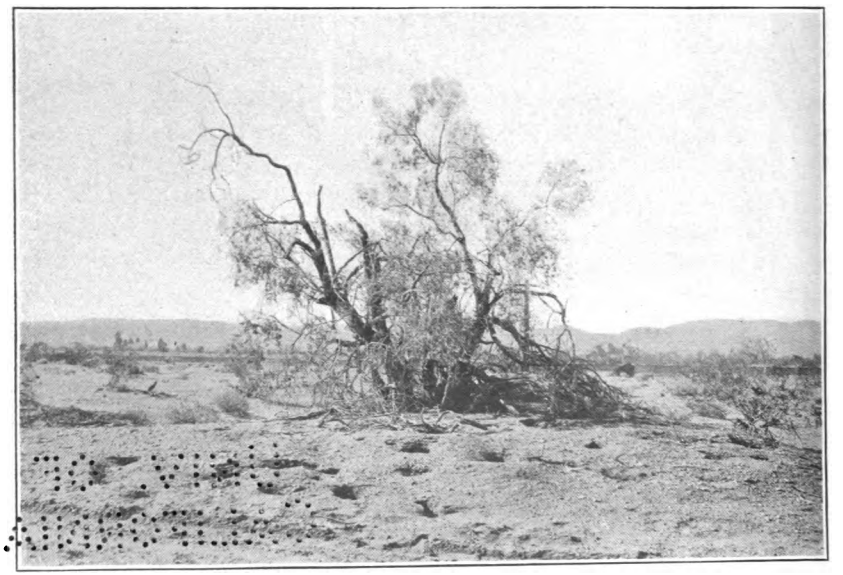

FIG. 2.—KANGAROO RAT MOUND (DIPODOMYS DESERTI).

Den of *Dipodomys deserti deserti*, showing typical wide, low mound with numerous entrance holes. This species excavates its den in soft, sandy soil. The tree is a species of *Dalea*.

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Key to Species of Dipodomys *in Arizona.*

a^1. Size much larger (hind foot and greatest length of skull more than 42 millimeters); tail tipped with white.

b^1. Upper parts dark brownish buffy; tail dark brownish or blackish with more sharply contrasted white tip; interparietal broader, distinctly separating mastoids (range in Arizona mainly southeastern part)---------- **Dipodomys spectabilis.**

b^2. Upper parts light ochraceous-buffy; tail pale brownish with less sharply contrasted white tip; interparietal narrower, reduced to mere spicule between mastoids (range in Arizona mainly southwestern part)---------- **Dipodomys deserti.**

a^2. Size much smaller (hind foot and greatest length of skull less than 42 millimeters); tail not tipped with white.

b^1. Hind foot with four toes---------- **Dipodomys merriami.**

b^2. Hind foot with five toes---------- **Dipodomys ordii.**

On account of the small size, *merriami* and *ordii* do not require detailed color comparison with the other two. The general color of the upperparts of *spectabilis* is much darker than that of *deserti;* whereas *spectabilis* is ochraceous-buff or light ochraceous-buff grizzled with blackish, *deserti* is near pale ochraceous-buff and lacks the blackish.

The color of the upperparts alone amply suffices to distinguish *spectabilis* and *deserti;* but the different coloration of the tail is the most obvious diagnostic feature. The near black of the middle portion of the tail, the conspicuous white side stripes, and the pure white tip make the tail of *spectabilis* stand in rather vivid contrast to the pale-brown and whitish tail of *deserti.*

The dens of the two larger species of *Dipodomys*—*spectabilis* and *deserti*—can be distinguished at a glance from those of the two smaller—*merriami* and *ordii*—by the fact that the mounds of the former are usually of considerable size and the burrow mouths are of greater diameter. On the Range Reserve *merriami* erects no mounds, but excavates its burrows in the open or at the base of *Prosopis*, *Lycium*, or other brush. The mounds of *spectabilis* are higher than those of *deserti*, the entrances are larger, and they are located in harder soil (Pl. III, Fig. 1). The dens of *deserti* are usually more extensive in surface area than those of *spectabilis*, and have a greater number of openings (Pl. III, Fig. 2).

DESCRIPTION.

GENERAL CHARACTERS.

Size large; ears moderate, ear from crown (taken in dry skin) 9 or 10 millimeters; eyes prominent; whiskers long and sensitive; fore feet short and weak; hind feet long and powerful, provided with four well-developed toes; tail very long, usually 30 to 40 per cent

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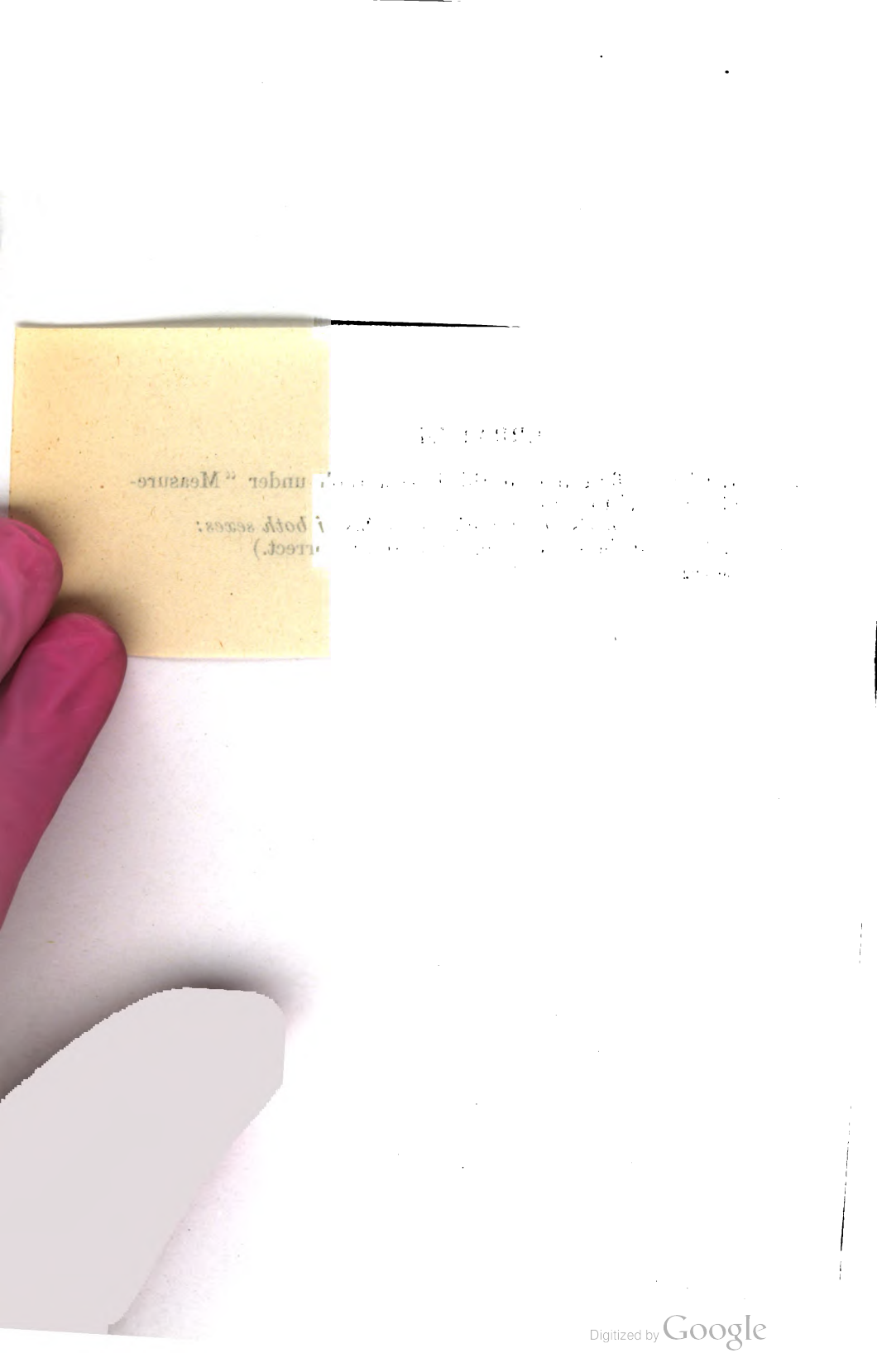
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ERRATUM.

Page 7. Change first line of third paragraph under "Measurements and weights," to read—

Average measurements of 30 adult specimens of both sexes:

(The first line of the succeeding paragraph is correct.)

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invading the yellow pine Transition where the soil was dry and sandy and the pine woods of open character. The same observer found it common in grassy and weed-grown parks among the large junipers, pinyons, and scattering yellow pines of the Bear Spring Mountains, N. Mex. Bailey calls attention to the fact that the animal apparently does not inhabit the lower half of the Lower Sonoran Zone, as it extends neither into the Rio Grande Valley of Texas nor the Gila Valley of Arizona. In extreme western Texas it is common at the upper edge of the arid Lower Sonoran Zone, and in this region does not enter the Upper Sonoran to any extent.

In July, 1914, Goldman found this kangaroo rat common on the plain at 4,600 feet altitude, near Bonita, Graham County, Ariz., and noted a few as high as 5,000 feet altitude on the warm southwestern slopes of the Graham Mountains, near Fort Grant. Apparently *spectabilis* reaches its upper altitude limit in the Burro Mountains, N. Mex., where Bailey has found it sparingly on warm slopes up to 5,700 feet, and at the western base of the Sandia Mountains, east of Albuquerque, N. Mex., where dens occur at approximately 6,000 feet.

About Tucson it is undoubtedly more common in the somewhat higher portions of the Lower Sonoran Zone, above the *Covillea* association, than elsewhere (Pl. IV, Figs. 1 and 2). A few scattered dens are to be seen in the *Covillea* belt, but as one rises to altitudes of 3,500 to 4,000 feet, and the *Covillea* is replaced by the cat's-claws (*Acacia* sp. and *Mimosa* sp.) and scattered mesquite (*Prosopis*), with the *Opuntia* becoming less abundant, kangaroo rat mounds come more and more in evidence. Here is to be found the principal grass growth supporting the grazing industry, and the presence of a more luxuriant grass flora is probably an important factor in the greater abundance of kangaroo rats, both *spectabilis* and *merriami*. In this generally preferred environment the desert hackberry (*Celtis pallida*) is one of the most conspicuous shrubs; clumps of this species are commonly accompanied by kangaroo rat mounds.

In order to ascertain whether the banner-tailed kangaroo rat has any marked preference for building its mounds under *Celtis* or some other particular plant, all the observable mounds were counted in a strip about 20 rods wide and approximately 4 miles long, an area of approximately 160 acres, particular note being taken of the kind of shrub under which each mound was located. Of 300 mounds in this area, 96 were under *Prosopis*, 95 under *Acacia*, 65 under *Celtis*, 11 under *Lycium*, 31 in the open, 1 about a "cholla" cactus (*Opuntia spinosior*), and 1 about a prickly pear (*Opuntia* sp.). There is apparently no strongly marked preference for any single species of plant. While both desert hackberry and the cat's-claws afford a better

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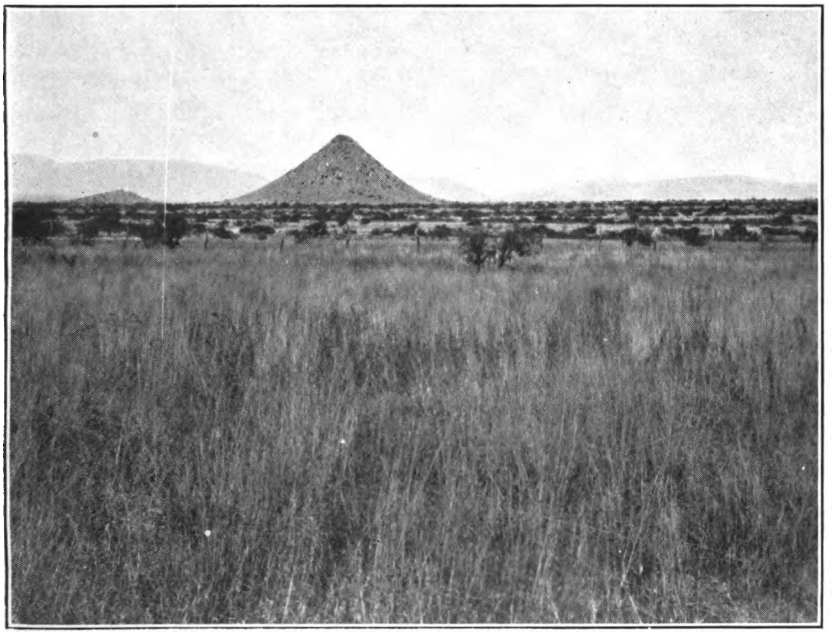

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FIG. 1.—RANGE CONDITIONS FAVORING KANGAROO RATS.

View on higher portion of Range Reserve, showing type of country where *Dipodomys s. spectabilis* is most abundant. Good growth of grama and needle grasses in October, following summer growth and before grazing off by cattle and rodents.

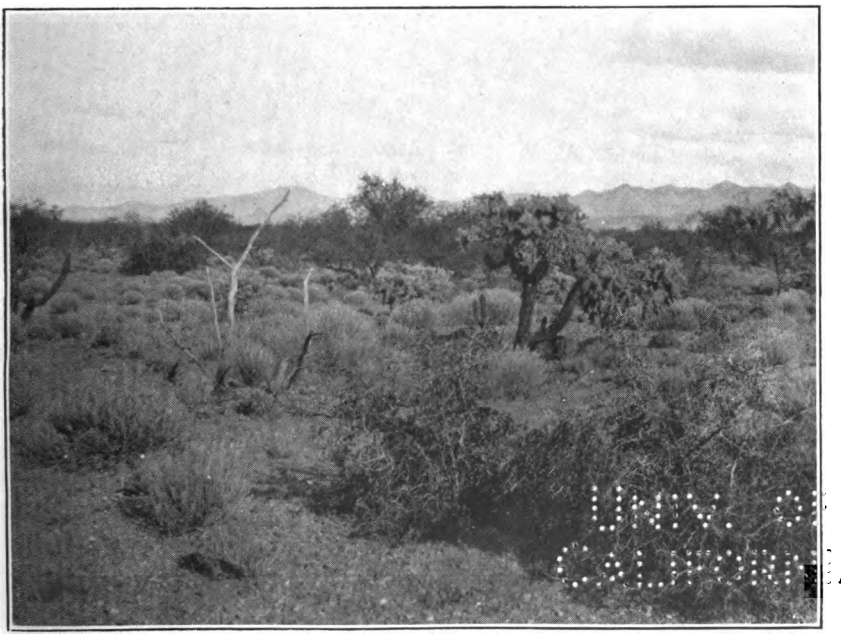

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FIG. 2.—RANGE CONDITIONS LESS FAVORABLE TO KANGAROO RATS.

View on lower portion of Range Reserve, where *Dipodomys s. spectabilis* is less abundant. Vegetation consists principally of *Lycium*, mesquite, rabbit brush, and cactus, there being very little grass.

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protection than mesquite—since cattle more often seek shade under the latter, and in so doing frequently trample the mounds severely—it appears that the general protection of a tree or shrub of some sort is sought by kangaroo rats, rather than the specific protection of the thickest or thorniest species.

The following records indicate particular habitat preferences of *spectabilis* as noted at different points in its range:

Occurs on open bare knolls exposed to winds, also on gravelly places at lower edge of foothills (Franklin Mountains, Tex., Gaut); here and there over the barest and hardest of the gravelly mesas (Bailey, Tex., 1905, 147); on open creosote-bush and giant-cactus desert (Tucson, Ariz., Vorhies and Taylor); on firm, gravelly, or even rocky soil on the grassy bajada land along the northwest base of the mountains, either in the open or under *Celtis*, *Prosopis*, *Lycium*, *Acacia greggii*, or other brush (Santa Rita Mountains, Ariz., Vorhies and Taylor); mounds usually thrown up around a bunch of cactus or mesquite brush (Magdalena, Sonora, Bailey); in heavy soil (Ajo, Ariz., A. B. Howell); loamy soil (Gunsight, Ariz., A. B. Howell); in mesa where not too stony (Magdalena, Sonora, Bailey); grassy plain (Gallego, Chihuahua, Nelson); in open valley and high open plains (Santa Rosa, N. Mex., Bailey); in grassy and weed-grown parks among the larger junipers, pinyons, and scattering yellow pines (Bear Spring Mountains, N. Mex., Hollister); on sand-dune strip (east side of Pecos River, 15 miles northeast of Roswell, N. Mex., Bailey); among *Ephedra* patches (San Juan Valley, N. Mex., Birdseye); in open sandy soil along dry wash (Rio Alamosa, N. Mex., Goldman); on sides and crests of bare, stony hills (Mesa Jumanes, N. Mex., Gaut); in open, arid part of the valley and stony mesas (Carlsbad and Pecos Valley, N. Mex., Bailey); about the edges of the plains of San Augustine and the foothills of the Datil and Gallina Mountains, and in the Transition Zone yellow-pine forest of the Gallina Mountains (Datil region, N. Mex., Hollister); on hard limy ridges (Monahans, Tex., Cary).

A. Brazier Howell notes that *spectabilis* occurs in harder soil than does *deserti*. This observation is confirmed by others, and seems to afford a conspicuous habitat difference between the two, for *deserti* is typically an animal of the shifting aeolian sands.

Usually, as on the Range Reserve, the rodents are widely distributed over a considerable area. Occasionally, as in the vicinity of Rio Alamosa, N. Mex., as reported by Goldman, they occur only in small colonies.

HABITS.

EVIDENCE OF PRESENCE.

MOUNDS.

One traveling over territory thickly occupied by the banner-tailed kangaroo rat is certain to note the numerous and conspicuous mounds so characteristic of the species, particularly if the region is of the savannah type, grassy rather than brushy. These low, rounded mounds occupy an area of several feet in diameter, and rise to vary-

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ing heights above the general surface of the surrounding soil, the height depending rather more upon the character of the soil and the location of the mound as to exposure or protection than upon the area occupied by the burrow system which lies within and is the reason for the mound.

A den in sandy soil in the open may be of maximum size in area occupied and yet scarcely present the appearance of a mound in any sense, due probably both to the fact that the sandy soil will not heap up to such a height over a honeycomb of tunnels as will a firmer or rocky soil, and also to its greater exposure to the leveling action of rains and the trampling of animals. These mounds are in themselves large enough to attract some attention, but their conspicuousness is enhanced by the fact that they are more or less completely denuded of vegetation and are the centers of cleared areas often as much as 30 feet in diameter (Pl. V, Fig. 1); and further that from 3 to 12 large dark openings loom up in every mound. The larger openings are of such size as to suggest the presence of a much larger animal than actually inhabits the mound. Add to the above the fact that the traveler by day never sees the mound builder, and we have the chief reasons why curiosity is so often aroused by these habitations.

On the Range Reserve the mounds are usually rendered conspicuous by the absence of small vegetation, but Nelson writes that in the vicinity of Gallego, Chihuahua, they can be readily distinguished at a distance because of a growth of weeds and small bushes over their summits, which overtop the grass. In the vicinity of Albuquerque, N. Mex., Bailey reports (and this was recently confirmed by Vorhies) that the mounds about the holes of *spectabilis* are often hardly noticeable. Hollister writes that in the yellow-pine forests of the Gallina Mountains the burrows are usually under the trunk of some fallen pine, both sides of it in some cases being taken up with holes, there being some eight or ten entrances along each side, the burrows extending into the ground beneath the log. In the vicinity of Blanco, N. Mex., Birdseye says that occasionally *spectabilis* makes typical dens but more often lives in old prairie-dog holes (*Cynomys*), or in holes which look more like those of *D. ordii*.

Runways and Tracks.

Still other features add to the interest in the dwelling places of *spectabilis*. Radiating in various directions from some of the openings of the mounds well-used runways are to be seen, some of them fading out in the surrounding vegetation, but others extending 30, 40, or even 50 or more yards to neighboring burrows or mounds (Pl. V, Fig. 2; Pl. VI, Fig. 1). These runways and the entrances to the mounds are well worn, showing that the inhabitants are at home and

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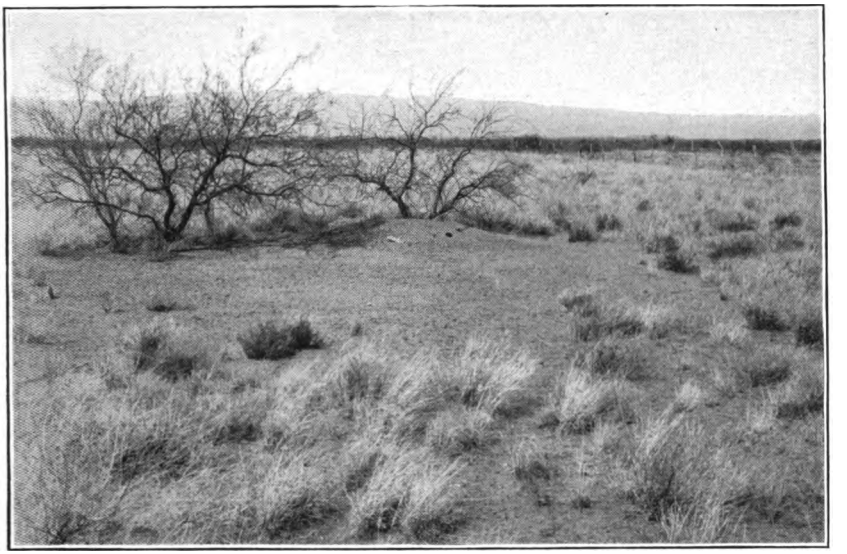

FIG. 1.—CLEARING ABOUT A MOUND.

A typica clearing about a mound of *Dipodomys s. spectabilis*, showing the autumnal denudation of the mound and surrounding areas in this instance about 30 feet in diameter.

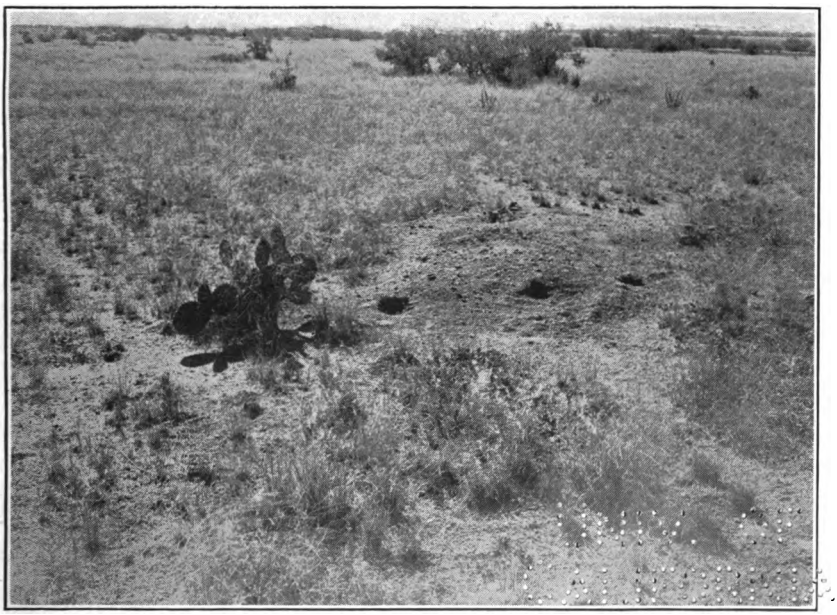

FIG. 2.—MOUND AND RUNWAYS.

A small mound of *Dipodomys s. spectabilis* in early autumn, showing runways radiating from the den. Evidences of activity may be noted in and about the surface of the mound.

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FIG. 1.—RUNWAY OF DIPODOMYS S. SPECTABILIS.

Well-traveled path leading from the main den, in the foreground, to a subsidiary burrow (see Fig. 2, below), about 30 feet distant, at apparent end of runway.

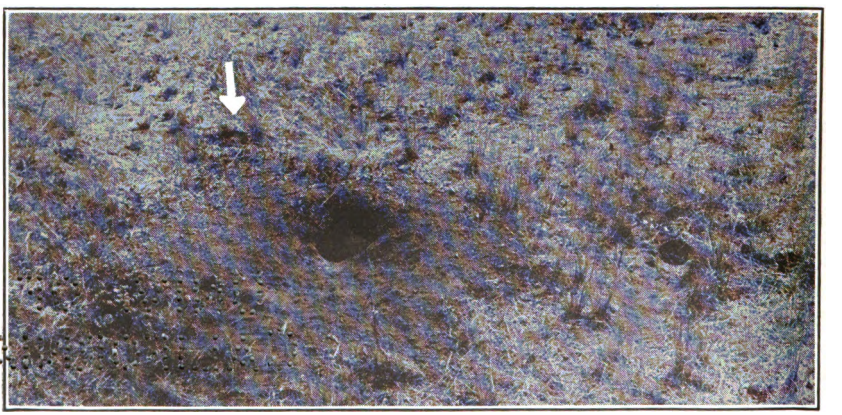

FIG. 2.—SUBSIDIARY BURROW OF DIPODOMYS S. SPECTABILIS.

Located at the end of the 30-foot runway shown in Figure 1, above. This has three openings, two in the foreground and the third a little to the rear and indicated by an arrow.

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are at some time of day very active. The worn paths become most conspicuous in the autumnal harvest season, when they stand out in strong contrast to surrounding grass. One usually finds not far distant from the main habitation one or more smaller burrows, each with from one to three typical openings, connected by the trail or runway system with the central den, and these we have called "subsidiary burrows" (Pl. VI, Fig. 2). These will be again referred to in discussing the detailed plan of the entire shelter system.

Examination of the runways and of the denuded area about a mound discloses an abundance of almost indecipherable tracks. The dust or sand is ordinarily much too dry and shifting to record clear footprints, and there are no opportunities to see footprints of this species recorded in good impressionable soil. Very characteristic traces of kangaroo rats may be readily observed in the dust about the mounds, however, and these are long, narrow, sometimes curving, furrows made by the long tails as the animals whisk about their work or play.

Signals.

If a scratching or tapping sound be made at the mouth of a burrow, even in the daytime, one is likely to hear a muffled tapping in response, and this may at times be heard while one is engaged in excavating a mound. It has a chirring or fluttering quality, described by Fisher as resembling the noise of a quail flying. Bailey (1905, 148) is of the opinion that it is used as a signal of alarm, call note, or challenge, a view which the present authors believe to be correct. During the winter of 1920–21, however, both Bailey and Vorhies discovered that this sound, or a very similar one, is made by the rapid action of the forefeet in digging. On one occasion in the laboratory the sound was given by one of a pair and was responded to at once by the other, the two being in separate but contiguous cages. This observation, however, could not be repeated. (Vorhies MS.)

One evening, while working in the vicinity of the Burro Mountains, N. Mex., Goldman heard a kangaroo rat near camp making this thumping noise. Taking a lantern, he approached the den, very cautiously, until within 10 feet. The kangaroo rat was just outside the entrance of one of its burrows, and though moving about more or less restlessly at first showed little fear, and kept up the thumping or drumming at intervals. When making the noise the animal was standing with the forefeet on the ground and the tail lying extended. The noise seemed to be made with the hind feet only, and the vibration of the feet could be seen. The tapping was kept up for a second or two at a time, the sounds coming close together and being repeated

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rhythmically after a very short interval, suggesting the distant galloping of a horse. After continuing in this way for a short time, the animal turned quickly about, with its head in the opposite direction, and began tapping. It appeared to pay little attention to the light, but finally gave a sudden bound and entered one of its holes about 4 feet from the one in front of which it had been standing.

Vorhies has repeatedly noted when watching for the appearance of a kangaroo rat at night that this sound invariably precedes the rodent's first emergence into the open, and often its appearance after an alarm, though when the storage season has begun and the kangaroo rat is carrying loads of grass heads or other material into its den, it regularly comes out without preliminary signaling. Vorhies has also observed it making the sound while on top of the mound, and certainly not digging, but was unable to see how it was made.

Voice.

No data concerning any call notes or sounds other than those described above are at hand, with the following exception: Price (in Allen, 1895, 213), who studied the habits of the animal in the moonlight, at Willcox, Ariz., says that a low chuckle was uttered at intervals; and Vorhies has had one captive female that would repeatedly utter a similar chuckle in a peevish manner when disturbed by day, and one captive male which, when teased into a state of anger and excitement, would squeal much like a cornered house rat. Vorhies has spent many moonlight hours observing kangaroo rats, but without ever hearing a vocal sound uttered by free individuals.

Daily and seasonal activity.

The kangaroo rat is strictly nocturnal. An observer watching patiently by a den in the evening for the animal's first appearance is not rewarded until darkness has fallen completely, and unless the moon is shining the animal can hardly be seen. Were it not for the white tail-brush of *spectabilis* and its white belly when upright on the hind legs and tail, one could not as a rule see the animal at all when it makes its first evening appearance. With the first streak of dawn activity usually ceases completely and much more abruptly than it began with the coming of darkness, but on a recent occasion Vorhies observed that a kangaroo rat which did not appear until near morning remained above ground until quite light, but not fully daylight. On removal of the plug from the mouth of a kangaroo rat burrow, one may sometimes see a fresh mass of earth and refuse shoved into the opening from within. As often as not, however, even this unwelcome attention does not elicit any response by day, the great majority of the burrow openings of this species, as observed by the authors, remaining permanently open.

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The ordinary activities of the kangaroo rat in southern Arizona can scarcely be said to show any true seasonal variation. The animals are active all the year in this region, there being neither hibernation nor estivation, both perhaps being rendered unnecessary by the storage habit, to be discussed in full later (pp. 15–16), and by the mildness of the winter climate. On any particular night that the weather is rainy, or the ground too wet and cold, activity is confined to the interior of the burrow system, and for this reason one has no opportunity to see a perfect imprint of the foot in freshly wet soil or in snow. On two or three of the comparatively rare occasions on which there was a light fall of snow on the Range Reserve a search was made for tracks in the snow. At these times, however, as on rainy nights, the only signs of activity were the pushing or throwing out of fresh earth and food refuse from within the burrow. This is so common a sight as to be complete evidence that the animals are active within their dens during stormy weather but do not venture outside. Trapping has again and again proved to be useless on rainy nights, unless the rain is scant and a part of the night favorable, in which case occasional individuals are taken. These statements apply to the Range Reserve particularly; the facts may be quite different where the animals experience more winter, as at Albuquerque, N. Mex., although in November, 1921, Vorhies noted no indications of lessened activity in that region.

PUGNACITY AND SOCIABILITY.

So far as their reactions toward man are concerned, kangaroo rats are gentle and make confiding and interesting pets; this is especially the case with *merriami*. This characteristic is the more surprising in view of the fact that they will fight each other so readily and so viciously, and yet probably it is explained in part by their method of fighting. They do not appear to use their teeth toward each other, but fight by leaping in the air and striking with the powerful hind feet, reminding one most forcibly of a pair of game cocks, facing each other and guarding in the same manner. Sometimes they carry on a sparring match with their fore feet. Biting, if done at all, is only a secondary means of combat. When taken in hand, even for the first time, they will use their teeth only in the event that they are wounded. The jaws are not powerful, and though the animals may lay hold of a bare finger, with the apparent intention of biting, usually they do not succeed in drawing blood. As Bailey says (1905, 148), they are gentle and timid, and, like rabbits, depend upon flight and their burrows for protection.

The well-traveled trails elsewhere described (p. 10) indicate a degree of sociability difficult to explain in connection with their pug-

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nacity toward each other. While three or four individuals may sometimes be trapped at a single mound, more than two are seldom so caught, and most often only one in one night. Trapping on successive nights at one mound often yields the larger number, yet in some cases the number is explained by the fact that two or three nearly mature young are taken, and the capture of several individuals at a single mound can not be taken to indicate that all are from the one den. Our investigations tend strongly to the conclusion that only one adult occupies a mound, except during the period when the young are in the parental (or maternal) den. In the gassing and excavating of 25 or more mounds we have never found more than one animal in a den, except in one instance, and then the two present were obviously young animals.

SENSE DEVELOPMENTS.

Without making special investigations through a study of behavior or other special methods, one can speak in only general terms regarding what appear to be the special sense developments of kangaroo rats. The eyes are large, as is very often the case in nocturnal animals, and when brought out into the bright light of day the rats perhaps do not see well. Yet, if an animal leaves a den which is in process of excavation, and follows one runway, even in bright sunlight, it makes excellent speed to the next opening, often a distance of several yards. Whether this is accomplished chiefly by the aid of sight or in large measure by a maze-following ability, such as experiments have shown some rodents to have, can not be stated without precise experimentation. Marked ability to follow a maze would not be at all surprising in view of the labyrinthine character of the underground passages which make up the normal habitation.

When watching beside a mound by moonlight one is impressed with the fact that the rats possess either a very keen sense of hearing or of sight, probably both. The very slightest movement or noise on the part of the observer results, with a timid individual, in an instantaneous leap for safety, a disappearance into the burrow so sudden as to be almost startling. All attempts to obtain flashlight photographs at the mounds were failures, the animal either having gotten completely out of the field before the light flashed following the pull of the trigger, or leaving merely an indistinguishable blur on the plate as it went, and this in spite of carefully hiding the trigger chain behind a screen. A slight noise accompanying the trigger action gave the alarm in one case, and in another the length of time of the flash was sufficient for the get-away. The marvelous quickness of the animal clearly indicates a remarkably short reaction time.

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Occasionally a bold individual is found, as in the case of one which came out repeatedly, even after being flashed twice in the same night.

Certain peculiar physical characteristics suggest a relationship to sense reactions. On these, however, the authors are not prepared to do more than offer suggestions for future work. The extremely large mastoids found in kangaroo rats suggest a connection in some way with special developments of the sense of hearing or of balance. It may be noted that an intermediate condition between the kangaroo rats and the majority of rodents in respect to this character is to be found in the pocket mice (*Perognathus*), which belong to the same family. Herein lies a field for some interesting experimentation and discovery.

The small, pointed nose might suggest a not overkeen sense of smell, and there appears no reason to believe that this sense is particularly well developed. However, the turbinals are very complex. The vibrissæ are long and sensitive, and may indicate a special development of the sense of touch as an adaptation to nocturnal habits and to life in an underground labyrinth. The long, well-haired tail doubtless serves as an important tactile organ as well as a balance.

MOVEMENTS AND ATTITUDES.

Movements and attitudes are characteristic. As a kangaroo rat emerges from the burrow a reason for the relatively large size of the opening is seen in the fact that, kangaroolike, the animal maintains a partially upright position. Its ordinary mode of progression is hopping along on the large hind legs, or, when in the open and going at speed, leaping. When moving slowly about over the mound, as if searching for food, it uses the fore legs in a kind of creeping movement. It appears to be creeping when pocketing grain strewn about, but close observation shows that the fore feet are then used for sweeping material into the pockets, reminding one somewhat of a vacuum cleaner. When it assumes a partially upright position the fore limbs are usually drawn up so closely that they can be seen only by looking upward from a somewhat lower level than that occupied by the animal. The slower movements of searching or playing about the mound are occasionally interrupted by a sudden leap directly upward to a height of 1½ to 2 feet, often with no apparent reason other than play. This is, however, a fighting or guarding movement, though indulged in for play. The play instinct seems to be well developed, and in evidence on any moonlight night when actual harvesting operations are not going on.

STORING HABITS.

Probably no instinct is of greater importance to the kangaroo rat than that of storing food supplies. When a crop of desirable seeds

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is maturing the animal's activities appear to be concentrated on this work. During September, 1919, when a good crop of grass seed was ripening following the summer rains, a kangaroo rat under observation made repeated round trips to the harvest field of grass heads. Each outward trip occupied from 1 to 1½ minutes, while the unloading trip into the burrow took only 15 to 20 seconds.

One individual in a laboratory cage, which had not yet been given a nest box, busied itself in broad daylight in carrying its grain supply into the darkest corner of the cage. When a nest box is supplied the individual will retreat into its dark shelter, and will only come forth after darkness has fallen unless forcibly ejected, but will store the food supplied.

In another case an animal escaped while being handled, and sought refuge behind a built-in laboratory table, where it could not be recovered without tearing out the table. For four days and nights it had the run of the laboratory. On the first night of its freedom it found and entered a burlap bag of grass seed that had been taken from a mound. A trail of seed and chaff next morning showed that it had been busily engaged in making its new quarters comfortable with bedding and food. After four nights of freedom it was captured alive in a trap, and later it was found that it had moved from the corner behind the table to the space beneath a near-by drawer, where it had stored about 2 quarts of the grass seed and a handful of the oatmeal used for trap bait.

BREEDING HABITS.

Observations on breeding habits have consisted mainly in taking records from the females trapped at all seasons of the year throughout the course of the investigation, and from examinations made during poisoning operations, and yet from this source the number of pregnant females taken or of young discovered is disappointingly small. The records indicate a breeding period of considerable length, extending from January to August, inclusive. It is possible that the length of the period may be increased by a second litter from the earliest breeding females in summer, but the large percentage of nonpregnant or nonbreeding animals which occurs throughout the season would indicate a wide variation in the time of breeding of different individuals.

Trapping in February and March for the purpose of securing greater numbers of female specimens, begun with the idea that these months were most likely to be the breeding months, has invariably yielded an unsatisfactory number of nonbreeding specimens and males. Unfortunately, the numbers of females secured in some months were not sufficient to be significant if worked out in per-

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centages of breeding and nonbreeding individuals, and this, coupled with the fact that the importance of recording carefully all nonbreeders was not at first recognized, makes it impossible to tabulate such information reliably. The total of females taken in April, for example, is only 3, of which 1 was breeding; while in June, during the course of poisoning operations, 45 females were examined, of which 21 were breeding.

Five breeding females were taken in January, all during the last three days of the month. One of these was a suckling female, the young of which were secured alive and were probably at least a week old when taken. This must have been exceptionally early for young, since of a number of adult kangaroo rats taken during the first week of January none have been found to be breeding. Two records from Vernon Bailey are as follows: May 19–June 8, 1903, young specimen in nest (Santa Rosa, N. Mex.); June 12, 1889, one female, two embryos (Oracle, Ariz.).

The considerable proportion (which we believe to be more than 50 per cent) of nonbreeding females taken during all those months in which breeding has been found to occur may also indicate an extended period of breeding, with a small percentage breeding at any one time. This period also furnishes ample time for the rearing of two litters a year by some females, but we have no evidence as to the occurrence of two litters. Young of the year, practically grown, are taken during and after the month of April.

The mammae are arranged in three pairs, pectoral, $\frac{1}{1}$; inguinal, $\frac{2}{2}$.

Kangaroo rats are among those rodents in which the vagina becomes plugged with a rather solid material, translucent, and of the consistency of a stiff gelatine, after copulation. This must occur very soon after coitus, since in those individuals taken in this condition no definite evidence of the beginning of development of embryos could be detected by examination.

The length of the gestation period of *spectabilis* is unknown. The young are born naked, a fact inferred by failure to find any fetus showing noticeable hair development, and from the conditions observed in such young as have been seen. A suckling female was taken by Vorhies, January 31, 1920, and her den immediately excavated in the hope of securing the young. Two juveniles were found in a special nest chamber (see p. 30). These were estimated to be perhaps two weeks old. A serious effort was made to raise the little animals by feeding milk with a pipette and keeping them warm with a hot water bottle, but they survived only 10 days, without the eyes having opened. The uneven temperature as well as the character of the food was probably responsible for their deaths. On February 3 they were measured and weighed, with the following results:

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	Weight (in grams).	Measurements (in millimeters).		
		Total length.	Tail vertebrae.	Hind foot.
No. 1	13.3	90	38	24
No. 2	12.6	93	38	24

At this stage the young were partially clothed with a coat of fine velvety fur, more especially on the bodies, the tails being still nearly naked. The body color was dark plumbeous, just the color of the dark underfur of the adult, or a shade darker, while the characteristic white markings of the adult stood out sharply as pinkish-white areas against the dark background (see Pl. IX, Fig. 2, at p. 32). The proportions were much as in the adult, except that the tails were relatively much shorter and the feet relatively longer.

Only one other record of young is at hand, that by Bailey, who secured the young after capture of a suckling female at Santa Rosa, N. Mex. In this case the litter contained only one. This was squeaking when found, but was not large enough to crawl away. Its eyes and ears were closed, and its soft, naked skin was distinctly marked with the pattern of the adult, the colors being as given for the other two. This juvenile lived only a week. Young less than half grown were not trapped or noted in our poisoning operations outside the dens.

Kangaroo rats, if *spectabilis* be representative, reproduce at a slow rate as compared with many other small rodents. We have records of 67 females with embryos or scars showing the number produced, and of the two litters of young described above. Of the 69 females thus recorded, 15, or 21.7 per cent, had but one offspring each; 52, or 75.3 per cent, but two each; while only 2 individuals, or 2.9 per cent, had three. Three young is the maximum litter recorded. This, taken in connection with the protracted breeding season and lack of sure evidence of the production of two broods a year, gives a surprisingly low rate of reproduction, indicating relative freedom from inimical factors.

Our breeding records for *merriami* are fewer than for *spectabilis*, but are very similar in every way so far as they go, both as to the time of year and number of young.

FOOD AND STORAGE.

Dipodomys s. spectabilis does not hibernate, so must prepare for unfavorable seasons by extensive storage of food materials. There are two seasons of the year, in southeastern Arizona at least, when storage of food takes place, namely, in spring, during April or May, and in fall, from September to November, the latter being the more important. For the periods between, the animal must rely largely

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on stored materials. Not infrequently a season of severe drought precludes the possibility of any storage. The summer and fall of 1918 was such a season on the Range Reserve (Pl. II, Fig. 2). If food stores are inadequate at such a time the kangaroo rats must perish in considerable numbers. Fisher found many deserted mounds in the vicinity of Dos Cabezos, Ariz., in June, 1894, which may be accounted for in this way. In 1921 Vorhies found all mounds within 4 or 5 miles of Albuquerque, N. Mex., deserted by *spectabilis*, resulting probably from overgrazing by sheep and goats during a succession of dry years. In the arid Southwest natural selection probably favors the animals with the largest food stores, and it is not surprising that the storing habit has been developed to a remarkable degree.

Some stored material is likely to be found at any time of year in any mound examined, the largest quantity usually in fall and winter, the smallest in July or August (Table 1, dens 1, 2, 14, and 24). Amounts found by different observers vary from a few ounces to several quarts or pecks, and stored materials taken from 22 mounds on the Range Reserve vary in weight from 5 to 4,127 grams (more than 9 pounds). This is exceeded by one lot from New Mexico, which totaled 5,750 grams (12.67 pounds). It is fairly evident that in seasons of scanty forage for stock the appropriation of such quantities of grass seeds and crowns and other grazing materials by numerous kangaroo rats may appreciably reduce the carrying capacity of the range. Studies of cheek-pouch contents and food stores taken from dens show that the natural food of *spectabilis* consists principally of various seeds and fruits, particularly the seeds of certain grasses. The study of burrow contents has been especially illuminating and valuable.

All of the stored material from 22 dens on the Range Reserve and from 2 near Albuquerque, N. Mex., has been saved and analyzed as to species as carefully as the conditions of storage would permit. Within the mound the food stored is usually more or less segregated by plant species, though the stores of material of any one kind may be found in several places through the mound, and often the material is mixed. In the latter case the quantities of the various species can only be estimated, but in the former the species may be kept separate by the use of several bags for collecting the seeds, and a fairly accurate laboratory weighing can be made later. Very frequently, the explanation of this separation of species lies in the different seasons of ripening, but sometimes where two species are ripe at the same time near the mound, one is worked upon for a time to the exclusion of the other. The one kind is often packed in tightly against the other, but with a very abrupt change in the character of the material.

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A number of the more interesting and representative results of the weighing and analyses of burrow contents are presented herewith in tabular form. The data for each den, or lot, shows in grams the quantity of stored material removed and the best estimate it was possible to make of the percentages or weights of the various species. When the weight was less than 5 grams, the mere trace of the species frequently is indicated in the following tables by the abbreviation "Tr."

TABLE 1.—*Analyses of plants stored by* Dipodomys spectabilis spectabilis *Merriam, obtained from examination of representative dens (all except Den 24 from U. S. Range Reserve, near the Santa Rita Mountains, Ariz.).*

DEN 1.

February 7, 1918. Burrow typical, located on bank of wash in partially denuded grass-land, *Bouteloua rothrockii* and weed type; soil sandy; burrow photographed in section (Pl. VII, Fig. 1).

Species stored.	Grams.
Bouteloua rothrockii	2,205
Bouteloua aristidoides (B. eriopoda and B. rothrockii, Tr.)	1,445
Plantago ignota	442
Eriogonum polycladon	35
Total	4,127

Four species of plants represented in burrow contents (Pl. VII, Fig. 2). Maximum quantity for single burrow in series of 22 from Range Reserve.

DEN 2.

March 9, 1918. Surroundings overgrazed and partially restored by complete protection. Red soil, with much coarse rough gravel and stone.

Species stored.	Grams.
Bouteloua rothrockii (nearly pure)	1,460
Bouteloua rothrockii (mixed with Aristida spp.)	945
Boerhaavia wrightii	660
Bouteloua rothrockii Bouteloua aristidoides Aristida divaricata Aristida bromoides	525
Kallstroemia laetevirens	Tr.
Heterotheca subaxillaris	Tr.
Plantago ignota	15
Fleshy fungi	10
Total	3,615

Eight species of plants represented by seeds. One species of fleshy fungus in addition.

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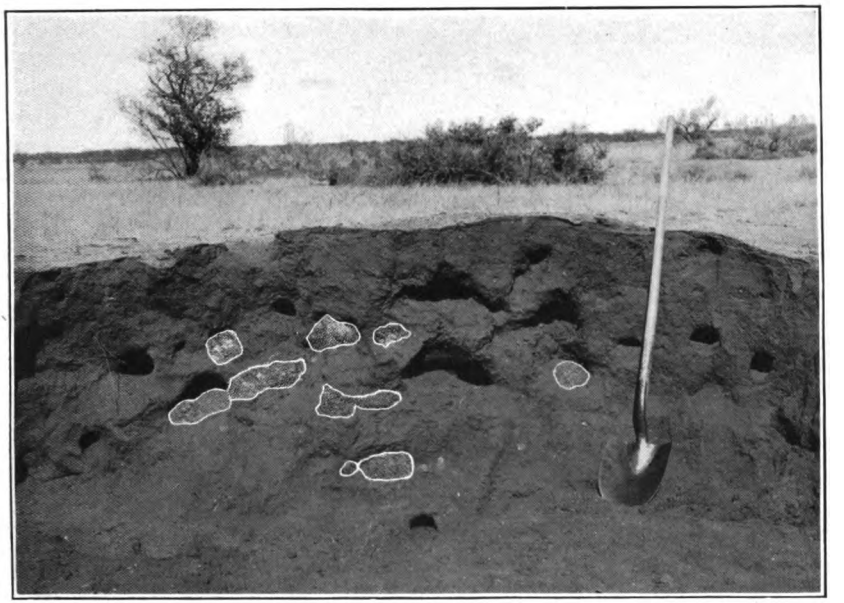

FIG. 1.—DEN EXCAVATED ON RANGE RESERVE.

Vertical section through Den No. 1, of Table 1 (p. 20), showing the complex system of burrows, some of them plugged with closely packed storage (outlined in white), the depth of the den, and the widened chambers centrally located.

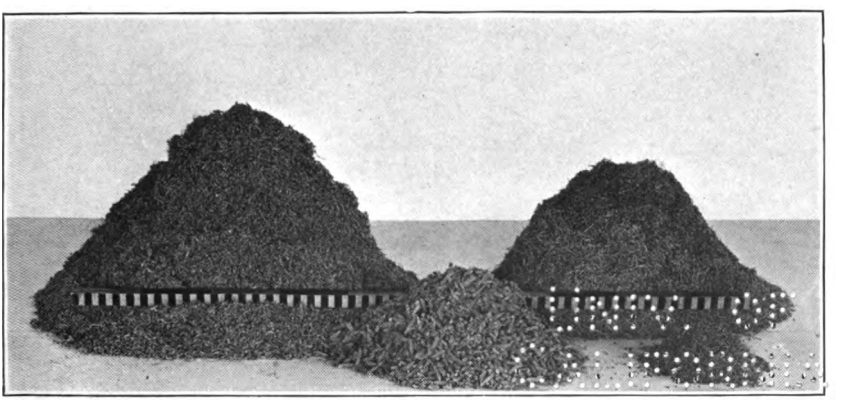

FIG. 2.—CONTENT OF EXCAVATED DEN.

Storage content of Den No. 1 (Fig. 1, above), showing the separate species of plants listed in Table 1. The rod is 1 meter long. The large pile on the left is composed of seed-laden heads of crowfoot grama (*Bouteloua rothrockii*), the large pile on the right consists of heads of six-weeks grama (*Bouteloua aristidoides*), the pile of heads in the center is desert plantain (*Plantago ignota*), and the smallest heap is composed of buckwheat-bush seeds (*Eriogonum polycladon*).

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DEN 4.

September 20, 1918. In *Calliandra* type. Stony or gravelly soil, red, nearly denuded of grass.

Species stored.	Per cent.	Grams.
Prosopis velutina		190
Mollugo verticillata (pure)		90
Anisolotus trispermus (mixed, but mostly of this genus)		50
Solanum elaeagnifolium (12 fruits)		2
Mollugo verticillata (inseparable)	50	400
Bouteloua rothrockii	1	
Bouteloua aristidoides	10	
Lepidium lasiocarpum	Tr.	
Polygala puberula	Tr.	
Ayenia microphylla	2	
Portulaca suffrutescens	1	
Aplopappus gracilis	Tr.	
Alternanthera repens	1	
Tridens pulchella	1	
Plantago ignota	33	
Panicum hallii	Tr.	
Fleshy fungi (puffballs)		2
Total		734

Fifteen species represented in addition to the fleshy fungi. No perceptible grass growth from the summer rains here, therefore dependent on a wide variety of scattering plants.

DEN 6.

October 17, 1918. Mixed type, partially denuded, no growth from summer rains. Sandy soil.

Species stored.	Grams.
Bouteloua rothrockii (crowns) (heads 1 to 2 per cent)	1,435
Bouteloua rothrockii (heads and crowns, about 50 per cent of each)	325
Bouteloua rothrockii (with small percentage of crowns)	315
Boerhaavia wrightii (with a few grass crowns)	150
Prosopis velutina	90
Solanum elaeagnifolium (3 fruits)	Tr.
Total	2,315

Four species represented. Count of 100 grams of stored *Bouteloua* crowns gives 1,700, or 17 crowns per gram. At this rate there were at least 27,000 crowns stored in this burrow. If a density of 250 plants to the square yard be assumed (a high estimate) these crowns represent the total *B. rothrockii* on 104 square yards of range surface. Further examination of the vicinity of this den showed that the surrounding area was not completely cleared, but was devoid of *B. rothrockii*, while still having *B. eriopoda* with crowns undisturbed.

DEN 11.

April 9, 1919. In partially denuded land where good spring growth of *Eschscholtzia* was in bloom at time of excavation. Stomach of *spectabilis* killed

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in this burrow contained a mass of fresh but finely comminuted green material, probably poppy leaves, strongly colored with yellow from blossoms. No summer growth here in 1918.

Species stored.	Grams.
Bouteloua rothrockii (crowns) (miscellaneous chaff, etc.)	107
Eschscholtzia mexicana (buds and flowers)	10
Anisolotus trispermus (leaves and pods)	
Gaertneria tenuifolia (leaves)	
Lupinus sparsiflorus (flowers)	
Solanum elaeagnifolium (2 fruits)	Tr.
Total	117

Six species represented, some only by leaves or flowers and not by seeds. *Such storage is never in large quantity.* The fresh storage material was weighed after becoming air dry. This illustrates a late spring condition, storage running low.

DEN 14.

August 8, 1919. Excellent summer growth all over range. This burrow in mixed growth, grasses and weeds.

Species stored.	Grams.
Miscellaneous portions of *green plants* of mixed species, *no seeds*	5

Representing minimum for any one of the 22 burrows studied. Active storage does not begin until September.

DEN 16.

October 17, 1919. In good grass, but mound overrun by a large *Apodanthera* vine.

Species stored.	Per cent.	Grams.
Aristida divaricata	90 to 95	58
Chamaecrista leptadenia	10 to 5	
Bouteloua rothrockii	Tr.	
Prosopis velutina		200
Apodanthera undulata		55
Total		313

Five species represented. Two species, *Apodanthera* and *Chamaecrista leptadenia*, new to storage records. Several whole fruits of *Apodanthera*, about 2 inches in diameter, stored in addition to seeds alone; seeds of this form not previously noted in burrows, but very abundant in this one, indicating importance of the factor of accessibility in storage.

DEN 19.

October 31, November 1, 1919. In good grass. Entire burrow system mapped (Fig. 2, p. 29).

Species stored.	Per cent.	Grams.
Aristida spp. (probably mostly *divaricata*)	98	1,813
Eriogonum sp	Tr.	
Bouteloua rothrockii	1	
Bouteloua aristidoides	1	
Panicum sp	Tr.	
Prosopis velutina		1,213
Total		3,026

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Five species represented, in addition to those of *Aristida*. Largest storage of *Prosopis* found. Mound was near a good-sized mesquite tree. No storage in subsidiary burrows.

DEN 21.

January 31, 1920. Male trapped here night of January 29, and suckling female trapped at same place and same opening of mound, night of January 30. Burrow excavated to secure young, which were found in special nest chamber.

Species stored.	Grams.
Aristida spp. (intimate mixture of undetermined species)	1,115
Eschscholtzia mexicana (from spring of 1919)	48
Opuntia (prickly pear, seeds only, no fruits)	10
Total	1,173

Three species represented. Prickly pear hitherto found as fruits only.

DEN 22.

January 1, 1921. Rather good grass growth here in summer of 1920. Burrow typical, sandy soil. Two skulls of former residents unearthed.

Species stored.	Grams.
Aplopappus gracilis (some B. rothrockii)	1,030
Astragalus nuttallianus	630
Bouteloua rothrockii (some A. gracilis)	530
Sida diffusa	30
Solanum elaeagnifolium (282 fruits)	53
Loeflingia pusilla	Tr.
Bouteloua aristidoides	Tr.
Plantago ignota	Tr.
Lupinus sparsiflorus	Tr.
Old storage (mostly Bouteloua aristidoides with traces of B. rothrockii and Aristida divaricata)	60
Total	2,333

Eleven species represented. First instance of quantity storage of *Aplopappus gracilis*. First occurrence of *Loeflingia pusilla* and *Astragalus nuttallianus*.

DEN 24.

November 8, 1921. On mesa northeast of Albuquerque, N. Mex., near base of Sandia Mountains. Fair grass growth here during preceding summer.

Species stored.	Grams.
Sporobolus cryptandrus strictus	5,455
Salsola pestifer	295
Total	5,750

Two species represented. The heads of *Sporobolus cryptandrus strictus* are retained to a great extent within the leaf sheaths. This necessitates the cutting of the stems into suitable lengths for carrying, and the stored material appears to be merely cut sections of the stems. Close examination, however, discloses the heads within, and shows that as in other instances seed storage is the end sought. These pieces are packed beautifully parallel like so many matches,

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and vary from a minimum length of 20 to a maximum of 37 millimeters, averaging about 30. Count of 2 grams of the above *Sporobolus* material shows that there are 125 separate cut sections per gram, or a total of approximately 680,000 pieces in this one lot of storage, indicating a remarkable activity on the part of the individual rat (Pl. VIII, Fig. 1).

The number of lots of storage (24) studied in detail, extending as it does over a period of three years with seasons of varying growth conditions, is not sufficient to permit the construction of a curve showing increase and decrease in quantity of stored material with growing seasons and intervals between; but the results indicate a very decided increase during the autumn storing season, and continuing large well into the winter, since some outside material can still be obtained until midwinter. From about February to April a decrease may be noted, followed, if the spring growth of annuals be good, by a slight increase; and we can very nearly predict the general character of the increases and decreases by the precipitation and consequent growth conditions.

TABLE 2.—*Quantity of storage per den correlated with time of year and growth conditions of preceding season (chiefly from United States Range Reserve near the Santa Rita Mountains, Ariz.).*

Den No.—	Date.	Quantity.	Preceding season.	Den No.—	Date.	Quantity.	Preceding season.
	1918.	*Grams.*			1919.	*Grams.*	
1	Feb. 7	4,127	Good.	14	Aug. 8	5	Good.
2	Mar. 9	3,615	Do.	15	Sept. 4	151	Do.
3	July 25	401	Poor.	16	Oct. 17	313	Do.
4	Sept. 20	734	Do.	17	Oct. 18	583	Do.
5	Sept. 21	2,520	Do.	18	Oct. 25	3,410	Do.
6	Oct. 17	2,315	Do.	19	Nov. 1	3,026	Do.
7	Dec. 20	1,247	Do.	20	Dec. 13	2,816	Do.
	1919.				1920.		
8	Feb. 7	1,600	Do.	21	Jan. 31	1,173	Do.
9	Mar. 13	370	Do.				
10	Apr. 7	180	Do.[1]		1921.		
11	Apr. 9	117	Good.[1]	22	Jan. 1	2,333	Fair.
12	May 7	208	Do.[1]	23	Nov. 7	1,685	Good.
13	May 11	1,590	Do.	24[2]	Nov. 8	5,750	Do.

[1] Changing from poor summer season of 1918 to excellent spring growth of 1919.

[2] From near the Sandia Mountains, N. Mex.; others from United States Range Reserve, near the Santa Rita Mountains, Ariz.

In presenting Table 2, showing quantity of storage per burrow correlated with the time of year and the character of the preceding growing season, the fact may be emphasized that the growing seasons in southern Arizona are two in number—early spring and midsummer. The spring season is the less important, the plants consisting chiefly of a variety of small annuals, while the important range grasses make their chief growth and head out almost exclusively in the July-August rainy season. It may be noted also that the actual

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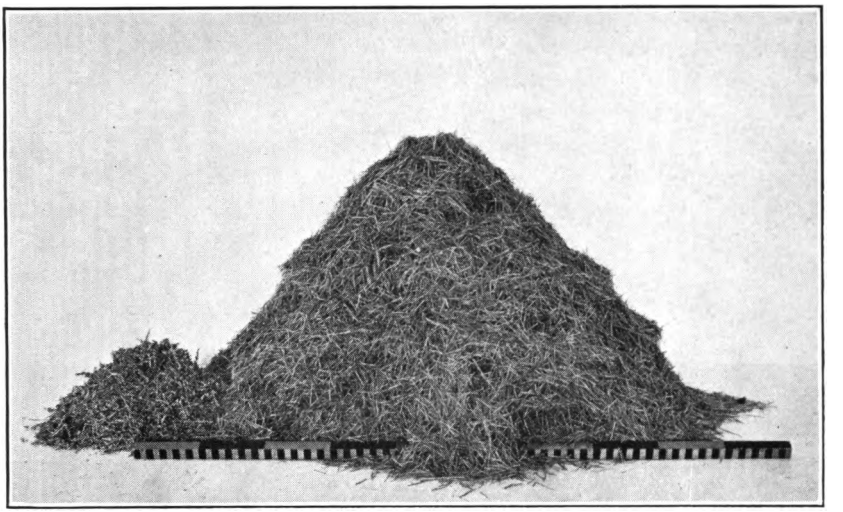

FIG. 1.—CONTENT OF DEN EXCAVATED IN NEW MEXICO.

Storage content of Den No. 24, of Table 1, from Sandia Mountains, N. Mex. This is the largest lot of storage taken in the course of the investigations. The larger pile consists wholly of a valuable grass, *Sporobolus cryptandrus strictus;* the smaller of Russian thistle (*Salsola pestifer*.)

FIG. 2.—GROWTH FOLLOWING ELIMINATION OF KANGAROO RATS.

The same mound as shown in Plate III, Figure 1, after three years of protection, the rodents having been killed out. Nearly as good grass recovery following poisoning operations occurred in the single excellent season of 1921.

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increases in storage appear somewhat after the growth period proper, since storing does not get well under way until the seed crop is mature. The banner-tailed kangaroo rat shows a marked adaptability to different foods available in the neighborhood of its burrows. It must, perforce, adapt itself and its storage program to the food that it can get, and this varies enormously with the climatic conditions of successive seasons. The large numbers present in suitable localities clearly indicate that the animal is successful in meeting the changing and sometimes extremely adverse conditions of its environment.

At times, more especially in the seasons of active growth, some of the green and succulent portions of plants are eaten. This was very noticeable in the spring of 1919, when a most luxuriant growth of Mexican poppy (*Eschscholtzia mexicana*) occurred. Stomachs at this time were filled with the yellow and green mixture undoubtedly produced by the grinding up of the buds and flowers of this plant. Small caches of about a tablespoonful of these buds were also found in the burrows at this time. Occasionally in spring one may find a few green leaves of various plants, *Gaertneria* very commonly, tucked away in small pockets along the underground tunnels, indicating that such materials are used to some extent. As has been shown in detail, however (Table 1), the chief storage, and undoubtedly the chief food, consists of air-dry seeds.

The character of the storage, the absence of rain for months at a time in some years, and the consequent failure of green succulents show that without doubt *spectabilis* possesses remarkable power, as to its water requirements, of existing largely if not wholly upon the water derived from air-dry starchy foods, i. e., metabolic water serves it in lieu of drink (Nelson, 1918, 400), this being formed in considerable quantities by oxidation of carbohydrates and fats (Babcock, 1912, 159, 170). During the long dry periods characteristic of southern Arizona, no evidence that the animal seeks a supply of succulent food, as cactus, is found; and if it may go for two, three, or six months without water or succulent food, it is reasonable to suppose that it may do so indefinitely. In the laboratory *spectabilis* ordinarily does not drink, but rather shows a dislike for getting its nose wet. During the periods of drought the attacks upon the cactuses by other rodents of the same region, as *Lepus*, *Sylvilagus*, *Neotoma*, and *Ammospermophilus*, become increasingly evident. The list of plant species thus far found represented in the storage materials of *spectabilis* on the Range Reserve is shown in Table 3.

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TABLE 3.—*List of all plant species found in 22 dens of* Dipodomys spectabilis. *on the United States Range Reserve, near the Santa Rita Mountains, Ariz., with approximate total weights.*

	Grams.
GRASSES.	
Aristida bromoides (six-weeks needlegrass)	536
Aristida divaricata (Humboldt needlegrass)	9,412
Aristida scabra (rough needlegrass)	344
Bouteloua aristidoides (six-weeks grama)	3,093
Bouteloua radicosa (grama)	1,269
Bouteloua eriopoda (black grama)	Tr.
Bouteloua rothrockii (seeds, 8,495; crowns, 3,517 grams) (crowfoot grama)	12,012
Festuca octoflora (fescue grass)	70
Panicum arizonicum (Arizona panic-grass)	11
Panicum hallii (Hall panic-grass)	Tr.
Pappaphorum wrightii	Tr.
Tridens pulchella	Tr.
Valota saccharata	Tr.
OTHER PLANTS.	
Alternanthera repens	Tr.
Anisolotus trispermus (bird's-foot trefoil)	186
Aplopappus gracilis	1,039
Apodanthera undulata (melon loco)	55
Astragalus nuttallianus (milk vetch)	630
Ayenia microphylla	Tr.
Boerhaavia wrightii	885
Chamaecrista leptadenia (partridge pea)	5
Echinocactus wislizeni (visnaga)	5
Eriogonum polycladon	35
Eschscholtzia mexicana (Mexican poppy)	250
Gaertneria tenuifolia (franseria)	Tr.
Collomia gracilis (false gilia)	Tr.
Heterotheca subaxillaris	Tr.
Kallstroemia laetevirens	Tr.
Lupinus sparsiflorus (lupine)	Tr.
Martynia altheaefolia (small devil's-horns)	12
Mollugo verticillata (carpetweed)	324
Oenothera primiverus (evening primrose)	15
Opuntia discata (prickly pear)	15
Loeflingia pusilla	Tr.
Lepidium lasiocarpum (peppergrass)	Tr.
Plantago ignota (plantain)	818
Polygala puberula (milkwort)	Tr.
Portulaca suffrutescens (purslane)	Tr.
Prosopis velutina (mesquite)	1,570
Sida diffusa (spreading sida)	30
Solanum elaeagnifolium (742 fruits) (trompillo, prickly solanum)	156
Puffballs and fleshy fungi (undetermined)	12

Total species, exclusive of fungi, 41.

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It will be seen from Table 3 that while a large number of species of plants are represented in the totals from so many dens, a majority of them are of very minor importance, and that the seeds of grasses are the principal storage and probably therefore the principal food material. Six of the most important species of grasses (disregarding species furnishing less than 5 grams) comprise 85.6 per cent of the total weight of storage from 22 dens. Crowfoot grama (*Bouteloua rothrockii*) stands first in quantity in the total, forming 39.4 per cent of all stored material, 46 per cent of the six important grasses, and 45 per cent of all grasses. The largest amount of storage of any one species of grass in any one den on the Range Reserve also is of this species, 2,205 grams[3] (Table 1, den 1, p. 20, and Pl. VII, Fig. 2). This is exceeded by a dropseed grass, *Sporobolus cryptandrus strictus*, which amounted to 5,455 grams in a lot from Albuquerque, N. Mex. (Table 1, den 24, and Pl. VIII, Fig. 1).

Of the species other than grasses found stored in these dens, mesquite beans (*Prosopis velutina*) are most important both by weight and number of dens containing them. The total for the 22 Range Reserve dens is 1,570 grams, or 35.9 per cent of the seeds other than grasses, but only 5.1 per cent of the total storage. In bulk mesquite beans do not loom up large, as they are probably the heaviest material stored. Sections of pods which must have been dragged into the burrows are found, some of them certainly being much too long for carriage in the pouches. The species of plant other than grass found in the largest quantity in any one den, however, was *Aplopappus gracilis*, not recorded in quantity from any den until the excavation of the twenty-second, and then found in a very large bulk of soft, fluffy material, with most of the seeds separated from the heads, and weighing 1,030 grams (Table 1, den 22).

Any of the food materials above listed are likely to be found in the cheek pouches, while in addition such extraneous matter as stones and feces have also been found. All species of plants stored are accessible in the immediate vicinity of the mound, and when any particular plant is found seeding in abundance in the vicinity of the den it is likely to be represented in the storage. Usually the animals can be readily trapped with almost any kind of grain bait, as oats, rolled oats, rolled barley, and wheat; and nut meats also are attractive, though we have no record of the storing of any true nut in the dens, such not being available in the range of the animal on the Range Reserve.

[3] This amount of dry grama grass seed (heads) amounts to approximately a bushel.

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The following plants not represented in the list stored by the kangaroo rat on the Range Reserve have been found in the cheek pouches or mounds of *spectabilis* in other localities:

Amaranthus palmeri, Sesuvium portulacastrum, and *Atriplex wrightii* (alluvial soil of Santa Cruz Valley, Continental, Ariz., Bailey).

Cut leaves and stems of a small sagebrush (Franklin Mountains, Tex., Gaut).

Gutierrezia heads (San Juan Valley, N. Mex., Birdseye).

Verbesina enceliodes, Portulaca oleracea, Bouteloua gracilis, and *Munroa squarrosa* (Rio Alamosa, N. Mex., Goldman).

Tops of buds of *Artemisia filifolia* (Mesa Jumanes, N. Mex., Gaut).

Tumbleweed (*Amaranthus graecizans*), Russian thistle (*Salsola pestifer*), *Munroa squarrosa,* and *Sporobolus cryptandrus strictus* (Sandia Mountains, Albuquerque, N. Mex., Vorhies).

BURROW SYSTEMS, OR DENS.

The burrow system, or den, in which *spectabilis* stores its caches of food materials, has its nest, and remains throughout the hours of daylight is a complicated labyrinth of tunnels. Ejection of refuse and soil from this retreat builds up the mound frequently referred to. These mounds are, as Bailey says, characteristic of the species, and are as unmistakable as muskrat houses or beaver dams, and as carefully planned and built for as definite a purpose—home and shelter. They are, furthermore, the most notable of all kangaroo rat dwelling places (Nelson, 1918, 400). They range in height from 6 inches to approximately 4 feet and from 5 to 15 feet in diameter.

The mound is built up not only through the cleaning out of chaff and other food refuse, but through extension and modification of the tunnels; old tunnels, entrances, and caches of musty food material are from time to time closed up and others excavated, repair and rebuilding being especially necessary after the collapse of portions of the den as a result of heavy rains or trampling by cattle. Ejected material is most commonly simply thrown out fan-wise from the openings, without much apparent effort to add to the height of the mound.

There are usually from 6 to 12 entrance holes in each mound opening into the subterranean burrow system, each hole from 4 to 5½ inches in diameter. These holes are nearly all situated a little above the surface of the surrounding soil, and as Price has suggested (in Allen, 1895, 213), this is doubtless a wise provision against flooding, as torrential rains sometimes occur in the kangaroo rat country.

Both Bailey and Nelson state that as a rule several of the holes are closed with sand or miscellaneous earth and old storage material during the daytime, but our observations on the Range Reserve are that such closing is only occasional. Many occupied dens have not

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a single opening closed. Further, night observations disclose that the inhabitant of the mound will appear from some one of the two or three most-used openings when night falls, and not necessarily from one which has been closed by day. Recently an opening closed one day was observed in use during the night, but was left open all the next day.

In attempting to determine whether there exist similarities of plan or system in the dens, it was considered advisable to map them with

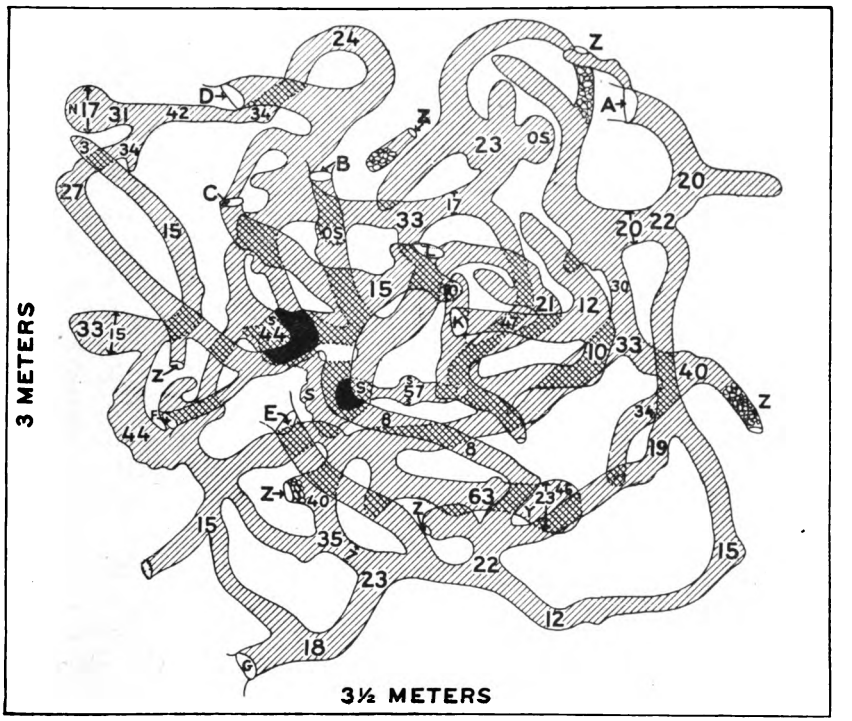

FIG. 2.—Diagram of a typical den of *Dipodomys spectabilis spectabilis*. Double shading indicates where one portion of tunnel lies above another and solid black a three-story arrangement; *A, B, C,* etc., active openings to surface; figures without arrows, depths in centimeters to tunnel roofs; figures with arrows, tunnel widths in centimeters; *N*, nest chamber; *S*, storage; *OS*, old storage; *Y*, probably an old nest chamber; *Z*, old, unused, or partially plugged openings.

some degree of accuracy. This we were enabled to do by laying off a square about a given mound, 2½ or 3 meters each way, and subdividing it into a series of small squares of half a meter on each side by drawing cross-lines on the surface of the ground over the top of the mound. One person then did the digging and exploring of the tunnels, as to direction and depth, while the other noted the results on coordinate paper (Figs. 2 and 3); the proper excavation and mapping of one of these workings occupied from four to eight hours for the two.

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While there is greater complexity in the larger, and probably older, mounds than in the smaller, all are extremely complicated and can only be described as labyrinthine in character. The tunnels wind about through the mound, rising and falling in vertical depth, intercommunicating frequently, but with occasional cul-de-sacs, and in places expanding into chambers, of which there may be three or four large ones. The stored materials are found in some, but not necessarily all, of these chambers, and may also occupy considerable lengths of ordinary tunnel, especially when the quantity present is large. Small evaginations of the tunnels frequently contain lesser caches, and it is in such pockets that bits of fresh material are placed during a growing season, or that grain supplied the previous night for bait is usually found.

The main masses of storage are most often found centrally located at depths of from 15 to 57 centimeters, although at times one may find a cache near the periphery of the system and as near the surface as 2 or 3 centimeters. In the latter case the materials are subject to wetting from rains, and consequent spoilage.

The major portion of the whole tunnel system is within about 50 centimeters of the surface of the mound, but usually some one branch tunnel goes to somewhat greater depth, and this is likely to be the one containing the nest; this is also likely to extend toward or beyond the periphery of the main system, and always ends blindly. Such a one, from which two young were taken on January 31, 1920, was at a depth of about 65 centimeters, and about 1½ meters beyond the periphery of the mound itself.

The individual tunnels average about 8 centimeters in height, and about 11 centimeters in width, though the variation, especially in width, is considerable. The expansions mentioned as being the chief places of storage are from 15 to 25 centimeters in diameter, and may or may not involve a considerable increase in height. They are frequently located at junction points of two or more branches of the tunnel system.

The nest cavity is a chamber of approximately spherical shape and from 17 to 23 centimeters in diameter. Chambers of this character were observed and noted as "old storage" in a number of cases. They were sometimes cut off from the rest of the habitation, and at first were supposed to contain abandoned musty storage. As experience in excavating and interpreting results has been gained we have concluded that these chambers in fact represent abandoned nests.

Bailey gives the dimensions of nest chambers observed in New Mexico as about 6 by 8 inches to 8 by 10 inches. The nest is composed of finer, softer, and more chaffy material than the regular

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storage. The chaff refuse from the food probably contributes largely to it, though some leaves of grasses not stored for food may also be found, and a nest, especially the one in use, may be distinguished, if excavating is carefully done, by the distinct cavity about the size

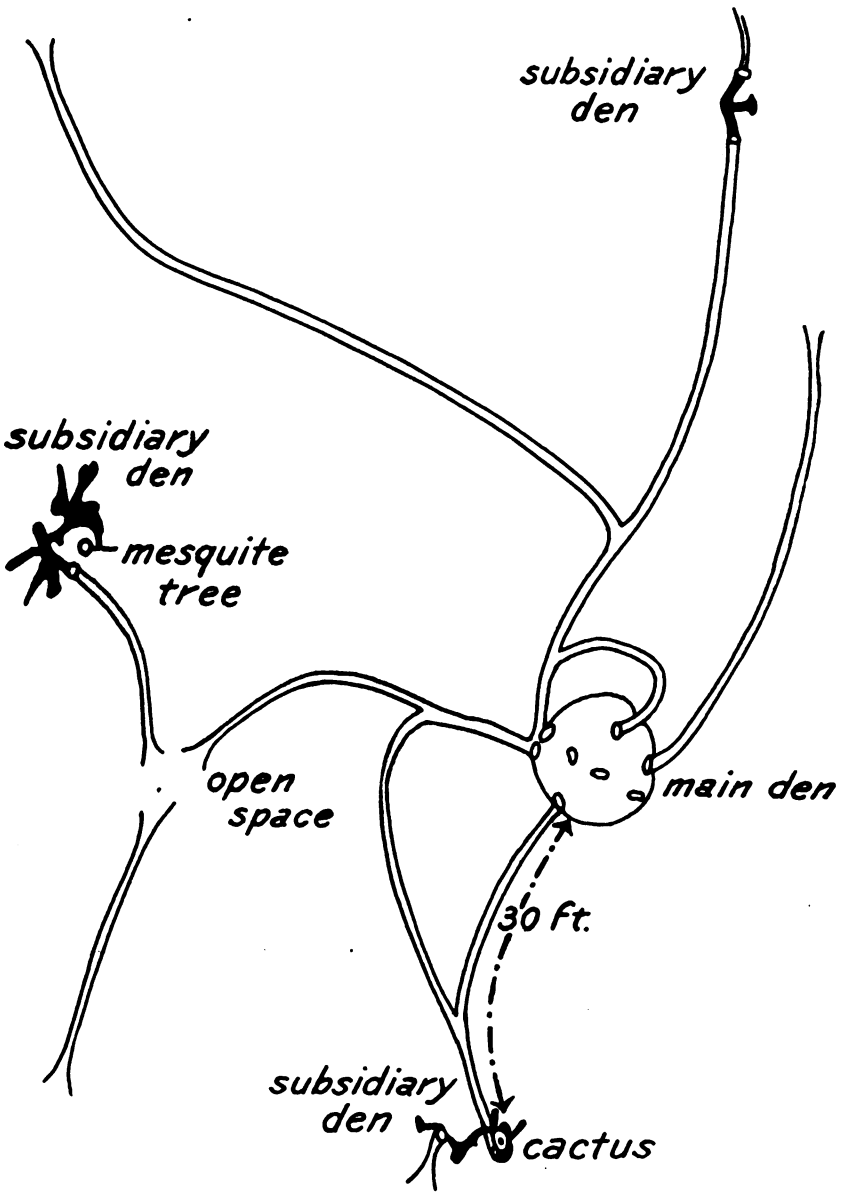

FIG. 3.—Diagram of the system of surface runways and subsidiary dens of *Dipodomys spectabilis spectabilis*. The underground tunnels of the main den were too complicated to illustrate on this scale, being very similar to those of Figure 2. The underground tunnels of the subsidiaries are shown in solid black. Some runways fade out in the grass in a manner that can not be indicated in a line drawing.

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of a fist in its interior (Pl. IX, Fig. 1). One may sometimes find this cavity distinctly warm from the recent presence of the inhabitant.

The walls or partitions between the chambers and tunnels are in places surprisingly thin, and it is no wonder that one is almost certain to break through in stepping on a mound, since the whole is a honeycomblike structure of from two to four stories in vertical plan, as shown by the transect of a mound in Plate VII, Figure 1. As Bailey writes, these partition walls are a mixture of earth and old food and nest material discarded years ago, resembling the adobe walls of the Mexican houses built of chopped earth and straw. This is the result of the continual ejection of refuse and earth as before mentioned, combined with the caving action of rains and disturbances from larger animals.

Apparently there are no special pockets for deposit of feces in *Dipodomys* burrows; such matter may be found throughout the den, and is more or less mixed with the food refuse which carpets practically the entire tunnel system. The nest and food stores are, however, clean and neat, the droppings being dry and, though present on the floor of a storage chamber, not actually mingled with the food. Evidently the animal does not clean up the floor litter before storing food material.

The entire system for any one den seems to consist not only of the burrows within the mound itself, as described, but of those small outlying ones which we have referred to as subsidiary burrows. These are two to four in number, and are connected with the main mound by the runways already mentioned. They often seem to be way stations on the runways connecting main mounds, and there is seldom any mound of earth whatever in connection with them. One entire den system, the home mound and three subsidiaries, was mapped after being excavated (Fig. 3), all having been carefully gassed with carbon bisulphide. The subsidiaries were simple and contained no storage. Two of them were shallow, while in the third a depth of 48 centimeters was reached. They appear to be merely places of refuge, though the well-worn trails connecting them with the main mound indicate regular use. These runways are conspicuous on the Range Reserve, and are apparently characteristic of mounds throughout the range of the animal. Dwellers in different mounds must have rather extensive social contacts, notwithstanding the enmity of individuals toward each other in captivity. The main mound, in this instance very complicated, was in one place three stories high, and we have found as many as four utilized stories; but as a rule there are two or three only.

Since collapses are rather frequent during rainy seasons, aside from the trampling previously referred to, the kangaroo rats, where

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FIG. 1.—KANGAROO RAT NEST AND YOUNG.

Nest and the two young, the ordinary number in the litter, of *Dipodomys s. spectabilis*, taken from den on January 31, 1920.

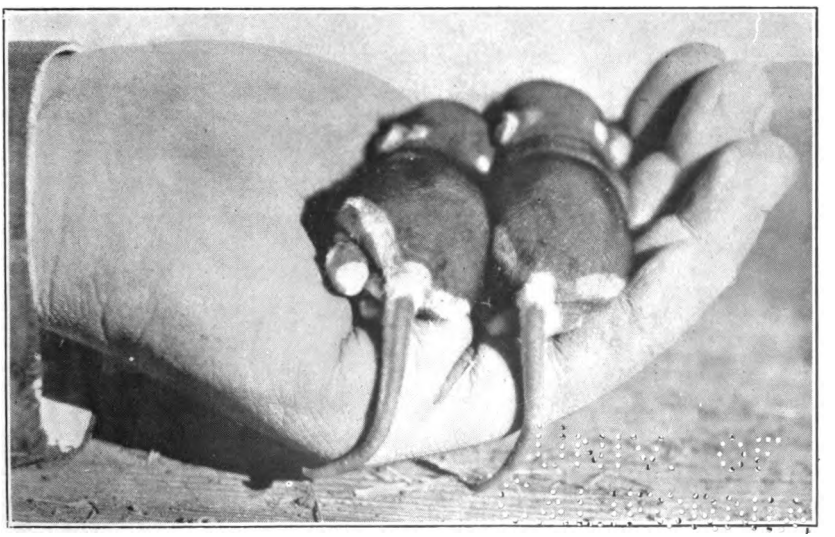

FIG. 2.—YOUNG OF THE KANGAROO RAT.

The same young as shown in Figure 1, above. They were probably about two weeks old, the pelage being short but with the white markings of the adult; the tails are relatively short and with scarcely any hair.

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abundant, as on the Range Reserve, may well be a factor in increasing soil porosity and fertility; for in the course of time they probably have succeeded in plowing and cultivating the whole surface layer of the soil. They may thus be a factor in ecologic succession, tending to improve the character of the soil and adapt it to another stage.

Doubtless their own workings afford the only shelter the animals know. In the course of our digging in one mound, the occupant, an adult male, did not forsake the den until the excavation was three-fourths completed; and even then it did not leave by a burrow leading away from our operations, but came toward us, escaped the active efforts of four individuals bent on its capture, and ran speedily along a used runway toward another burrow several meters distant. A sack had been stuffed in the mouth of this, however, and, baffled, the rat then returned to the original burrow and was captured. Observations on other rats thus driven from the home mound indicate that they are very familiar with the runways of the vicinity of the mound and the various subsidiary burrows, and it is a question whether they need to see clearly to follow these runs. Apparently they never attempt to escape by forsaking their well-traveled runways. Tests of the maze-running ability of these animals by animal-behavior experts would be of extraordinary interest, in view of the character of the homes which they always inhabit and the network of runs on the outside.

COMMENSALS AND ENEMIES.

COMMENSALS.

It is doubtful whether any animals live in a truly commensal relationship with *spectabilis*, but of not unfriendly associates there are a great number. It is the experience of Bailey, corroborated by observations of Vorhies on living animals, that these kangaroo rats are active in defending their caches of food, and will even fight individuals of the same species savagely and to the death. One moonlight night a strange individual was liberated on a mound. It deliberately entered one of the openings, but after about two minutes' time made an exceedingly rapid exit, running rapidly out of sight as if pursued, though the owner of the home did not appear outside of the burrow. There can be little doubt that the stranger was precipitately ejected by the owner. We suspect, though this is a point difficult to prove satisfactorily, that *merriami* does not always store food supplies for itself, but visits the burrows of *spectabilis* regularly to pilfer the seed stored therein. The observed facts thus far recorded which suggest this are that in no *merriami* burrow examined has a store of food been found, and also that in

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trapping for *spectabilis* on its own characteristic mounds one catches a large percentage of *merriami*.

On two separate occasions Vorhies has observed the smaller species running over the mounds of the larger, actually carrying away the grain which had been placed to entice the larger when it might appear. (In these cases the larger species did not put in an appearance until near morning.) Furthermore, the dens of *merriami* are often connected by distinct runways with those of *spectabilis*, indicating much traveling or visiting. That this is probably not friendly visiting is suggested by the certainty with which an individual of the larger species will strike and kill one of the smaller when they are placed together in the same inclosure. The word "thief" expresses this suspected relationship better than would the term "parasite."

It is not to be expected that such obvious shelter retreats as the mounds of *spectabilis* should fail to attract the attention of other animals. We have found a small gecko (*Coleonyx variegatus*), scorpions of two or three undetermined species, and certain insects (of the Order Orthoptera) to be very common inhabitants of the dens. With the exception of the parasitic insects the most common are wingless locustids (*Ceuthophilus* spp.) and the peculiar wingless females of a species of cockroach (*Arenivaga erratica*). These two are seldom absent when a burrow is excavated, the female cockroaches being abundant, although the winged males have never been taken in the burrows.

Cary's observations at Monahans, Tex., and those of others at numerous localities, combined with our own, show that at various times the dens furnish protection and shelter for various species of cottontail rabbits (*Sylvilagus*), ground squirrels (*Citellus* and *Ammospermophilus*), wood rats (*Neotoma*), grasshopper mice (*Onychomys*), rattlesnakes (*Crotalus*), and most of the common lizards. Of these the ground squirrels *Citellus tereticaudus* and *Ammospermophilus harrisii* are most often noted on the Range Reserve using the dens as a retreat, the *Ammospermophilus* seldom being observed to enter any other kind of burrow. It should be added that the total observations include dens which have been deserted by their rightful owners.

NATURAL CHECKS.

The enemies of the kangaroo rat are not determined in detail, or as to relative importance, but the badger (*Taxidea taxus berlandieri*) and the kit fox, or swift (*Vulpes macrotis neomexicana*), may well be foremost. Dens which have been deeply excavated by badgers are frequently seen, and sometimes two or three badger tunnels penetrate one burrow system. Dens thus despoiled are

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probably soon reoccupied even if the original owner is captured, and in the course of a few months the reworking of the abode obliterates the signs of destruction.

Droppings of the kit fox show an abundance of bones of small mammals of kangaroo rat size, among them those of *spectabilis*.

Bobcats (*Lynx baileyi*) and coyotes (*Canis mearnsi*) probably are a prejudicial factor. Skunks may sometimes be able to surprise the kangaroo rats, but probably not often. The western horned owl (*Bubo virginianus pallescens*), the barn owl (*Tyto alba pratincola*), and perhaps others may well be among the most feared enemies, but no special investigation of owl pellets on the reserve has been possible. In 592 barn-owl pellets from California were found remains of 230 kangaroo rats, only one other rodent being represented by a larger number (McAtee, 1921, 258).

Much more information on enemies is needed. The relatively low rate of reproduction (see p. 18) indicates comparative freedom from inimical factors.

PARASITES.

Dipodomys s. spectabilis is regularly infested with a species of flea, *Ctenophthalmus* sp. Seldom or never is a specimen taken in reasonably fresh condition without some of these parasites present on its body, though of course they desert the body of the host after it becomes cold, and hence dead specimens left too long may be free from them. The den conditions are ideal for the breeding of this parasite, because of the great quantities of fine, dusty, organic refuse littering the tunnels and furnishing food and refuge for the larvæ. As demonstrated to us by F. C. Bishopp, of the Bureau of Entomology, a handful of this refuse taken from the floor of a burrow within arm's length of the entrance is almost certain to contain these larvæ.

Less regularly present, perhaps because of its different life history, is a small tick, *Trombicula* sp. At times this parasite is very common, being present on nearly every individual rat, and at other times specimens are difficult to find; it appears to be more commonly present in summer and fall than at other seasons, and is found attached chiefly to the ears.

No internal parasites have been detected. The nocturnal and fossorial habits of the animal seem to give complete protection against a form of parasite which is very common among some other rodents of the Range Reserve, notably *Lepus* and *Sylvilagus*. Nearly all rabbits are infested with "warbles," the larvæ of a species of bot-fly, *Cuterebra* (family Oestridae). Other small mammals also are occasionally parasitized by the *Cuterebra*, but in the handling and examination of perhaps 200 or more individuals of *spectabilis* and *merriami*, we have yet to find a single case of infestation by an oestrid fly.

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ABUNDANCE.

One's first impression of a well-occupied *spectabilis* area is that a large family must inhabit each den, but, as previously mentioned, we have gradually been compelled to shift from this conception to the idea of but a single animal to a mound, except when the young are present. Therefore a census of the adult kangaroo rat population can readily be made, simply by counting the mounds. Such a census affords at least a conservative estimate of the number of adult individuals occupying a given area.

The first estimates of abundance on the Range Reserve were from actual counts of dens on areas measured off for experimental fencing, and gave the figure of about two mounds to the acre. From time to time rough estimates were made on different portions of the pastures, and these checked well with the above. Later still, a careful count showed 300 mounds on approximately 160 acres (see p. 8), or 1.87 mounds per acre. Nine areas of 2 acres each, representing different environmental conditions, were later selected in different portions of the Range Reserve, and the dens accurately counted. The number of dens per 2 acres varied from none to a maximum infestation of 12, neither extreme occurring over large areas. The total number of dens was found to be 43 on the 18 acres, or an average of 2.38 dens per acre.

From all these estimates it may fairly be concluded that two mounds, or two animals, per acre is a conservative estimate for the infestation of the entire Range Reserve, with the possible exception of small areas at its upper edges, where the altitude limit of *spectabilis* is passed. It is, however, impossible to estimate the area of the State infested with kangaroo rats, for some large stretches of fine grassland show no kangaroo rats whatever, while others have more than are present on the reserve; and we have no estimates of the extent of either type.

ECONOMIC CONSIDERATIONS.

In May, 1894, Fisher found a ranchman at Willcox, Ariz., who complained more bitterly of the depredations of *spectabilis* than of those of any other mammal.

On the United States Range Reserve the food material appropriated by the kangaroo rat during good years is inappreciable. There is such an excess of forage grass produced that all the rodents together make very little difference. But with the periodic recurrence of lean years, when drought conditions are such that little or no grass grows, the effects of rodent damage not only become apparent, but may be a critical factor determining whether a given number of domestic animals can be grazed on the area (Pl. VIII, Fig. 2).

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With two kangaroo rats to the acre (1,280 per square mile), there would be 64,000 animals on the 50 square miles of the Range Reserve. If each rat stores 4 pounds of grass seeds and crowns and other edible forage during the season (and in severe seasons we find that more crowns are stored than under ordinary conditions), a total of 256,000 pounds, or 128 tons, of edible forage are rendered unavailable to stock. In dry years it is probable that this amount of forage would be of critical importance. Allowing 50 pounds of food a day for each steer, the forage destroyed would be sufficient to provide for the needs of one steer for 5,120 days, or for the needs of 14 steers for one year. On a stock ranch the size of the Range Reserve this might mean the difference between success and failure.

It seems not unlikely, therefore, that during seasons of drought the banner-tailed kangaroo rat, where it is abundant on the grazing ranges of the Southwest, may be a factor of critical importance in relation to forage production and carrying capacity. It must be remembered, moreover, that the stored material consists largely of seeds, so that this loss is of greater importance than would be the case were it ordinary forage. Some of the range grasses of this region found in greatest quantity in the stored material depend in large part, under certain conditions, upon seed reproduction. Rehabilitation of a depleted range after severe drought and consequent close grazing and trampling is retarded by the heavy toll of seed taken by the kangaroo rats.

CONTROL.

Kangaroo rats may be easily eradicated by the use of the poisoned grain used for prairie-dog control by the Biological Survey and the University of Arizona Extension Service. This can be obtained by application to the State representative of the Biological Survey or to the local county agricultural agent, or may be mixed as follows:

Formula for poisoned bait.—Dissolve 1 ounce of strychnine sulphate in 1½ pints of boiling water. Add 1 heaping tablespoonful of gloss starch, previously mixed with a little cold water, and boil until a clear paste is formed. Add 1 ounce of baking soda and stir to a creamy mass. Add ½ ounce of glycerine and ½ pint of corn sirup and stir thoroughly. Pour over 16 quarts of rolled barley and mix well until every grain is evenly coated. Allow to dry before using.

In bushel quantities use as above directed, 2 ounces of strychnine, 2 ounces of soda, 1 ounce of glycerin, 1½ ounces of starch, 1½ quarts of boiling water, and ⅝ pint of corn sirup.

Scatter poison, when the natural food of the kangaroo rat is scarce, on clean hard places near the holes, 1 quart to 50 holes.

If powdered strychnine alkaloid is used, prepare the hot starch paste first. Then sift strychnine and baking soda, previously thoroughly mixed, into the hot starch paste and stir to a creamy mass. Proceed as in the above directions with sirup, glycerin, etc.

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Use this poison within five days after mixing or retain in air-tight containers.

Caution.—All poison containers and all utensils used in the preparation of poison should be kept *plainly labeled* and *out of reach of children*, irresponsible persons, and live stock.

A spoonful of the poisoned grain scattered about the used entrances of a mound is sufficient, and prebaiting is not necessary, as with prairie dogs.

A word of caution should perhaps be offered in connection with control measures. As man has come to occupy a greater portion of the earth's surface, and as he has become more and more the master of his environment, he has inevitably disturbed the relationships of the birds and mammals about him, has upset the balance of nature. If he kills the carnivorous species because of their depredations on game and live stock he must be prepared to cope with the increased hordes of rodents which feed on vegetation and on which the carnivorous animals act as a check. If he destroys the rodents, he may remove the checks on certain noxious plants or insects. One control measure often necessitates the adoption of another.

This is not to argue against control measures, for if our harmful species were not controlled, agriculture in many sections would be impossible. Control measures, however, should be scientifically founded and applied. The indiscriminate slaughter of supposedly harmful species of birds and mammals in the guise of benefiting agriculture may do far more harm than good. Many of the species which do some harm do far more good. The exact status of each suspected species should be carefully determined through an adequate scientific investigation. If the species is condemned, sound control measures should be thoroughly applied.

In grazing districts or in areas devoted to intensive agriculture the death sentence should probably be passed on the banner-tailed kangaroo rat. It should be recalled, however, that this is the largest and one of the handsomest of all its family, and that it is one of the most characteristic and interesting of all the desert fauna; where extensive grazing or agricultural operations are not undertaken, therefore, we feel that the kangaroo rat should be let alone, unless its presence threatens infestation of valuable agricultural or grazing lands.

SUMMARY.

(1) Kangaroo rats may be separated with ease from all other mammals; the long tail and short and weak fore feet separate them from the pocket gophers; the white hip-stripe distinguishes them from the pocket mice. The decidedly larger size and the white-tipped tail separate *Dipodomys spectabilis spectabilis* and *D. deserti* from *D.*

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merriami and *D. ordii*. The darker color and vividly contrasted black-and-white tail of *spectabilis* distinguish it from *deserti*.

(2) *Dipodomys s. spectabilis* occurs in the open arid country of portions of the Lower and Upper Sonoran Zones of Arizona, New Mexico, Texas, Sonora, and Chihuahua. It lives in harder soil than does *deserti*, and builds more conspicuous mounds.

(3) There is no evidence of intergradation or hybridization between *spectabilis* and *deserti*.

(4) *Dipodomys s. spectabilis* is nocturnal; it is gentle, and does not offer to bite when taken in the hand; is silent for the most part; active; somewhat sociable with its fellows, but fights in defense of its food stores; progresses chiefly by leaping; signals by a drumming or tapping on the ground with its hind feet.

(5) The breeding season of *spectabilis* begins in January and continues into August. Whether more than one litter is raised in a single season is unknown. The number of young in each litter varies from 1 to 3, averaging 2.

(6) *Dipodomys s. spectabilis* does not hibernate, but provides food stores, mostly seeds, for use during seasons when food would be otherwise unavailable. Storage in each den varies in quantity from 5 grams (about $\frac{1}{6}$ ounce) to 5,750 grams (12.67 pounds). Materials stored include several important forage plants; for example, various species of *Bouteloua* and *Aristida*, with *B. rothrockii* (crowfoot grama) the most important. Accessibility and abundance of different plants have much to do with the kinds of storage found.

(7) The dens of *spectabilis* are the most notable of all kangaroo rat dwelling places. They range from 6 inches to 4 feet in vertical height, and from 5 to 15 feet in diameter. Here the kangaroo rat has its home, shelter, and food-storage chambers. Within the den is found a tortuous network of burrows, with many storage and some nest chambers, the whole arranged so as to be two to four stories high.

(8) *Dipodomys s. spectabilis* is not of great economic significance, except locally, in ordinary seasons. During periods of extreme drought it may be of critical importance on grazing areas from the standpoint of the carrying capacity of the range.

(9) Kangaroo rats are easy to poison by following the same formula as that used by the Biological Survey for destroying prairie dogs.

(10) In many places unsuited to extensive grazing or agriculture *spectabilis* does no appreciable damage. It is one of the most interesting of all the rodents peculiar to our Southwestern deserts, and should not be molested except where it is destructive.

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SUNBURN AND APHID INJURY OF SOYBEANS AND COWPEAS

By Frederick Gibson
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Tucson

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SUNBURN AND APHID INJURY OF SOYBEANS AND COWPEAS

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INTRODUCTION

In a country where the soil is naturally deficient in organic matter, the problem of green manuring is important. For the purpose of supplying this need, and also as cover and forage crops, cowpeas *(Vigna sinensis)* and soybeans *(Soja max)* have been introduced into Arizona. Since the value of these plants for green manure, cover, and forage crops depends chiefly on the production of abundant foliage, any condition which favors injury to the green parts must be taken into account in the selection of varieties, and therefore susceptibility to sunburn and to parasitic diseases, which may result in the destruction of a large part of the leaf surface, are factors which must be considered.

During the fall of 1920, the attention of the writer was directed to a spotting of the leaves of cowpeas and soybeans growing on the Salt River Valley Farm near Mesa, Arizona. Indications of sunburn as well as the presence of aphids and a dense fungal growth, in spots, led to the cultural and histological studies that are described in this paper. It is hoped that the results may prove helpful in the selection of varieties of cowpeas and soybeans suited to the semi-arid conditions that prevail in Arizona and other southwestern states. In pursuing the investigation, field studies were supplemented with laboratory work and with inoculations of plants grown in the greenhouse at the University of Arizona at Tucson.

FIELD STUDY

In the spring of 1921, the Department of Agronomy of the Experiment Station planted plots of soybeans to determine the effect of the time of planting on the amount of growth and on the quantity and quality of the seed produced, and these plots were placed at the disposal of the writer for pathological study. The varieties used in the plots were Otootan, Biloxi, Virginia, and Mandarin. Planting was

The author gratefully acknowledges the assistance and the advice of Professor J. G. Brown, Plant Pathologist of the Agricultural Experiment Station, under whom this work was instituted as a thesis for the degree of Master of Science.

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begun on April 5 and was continued on the first and fifteenth days of each month following until August 15. All four varieties were planted on each of these dates. Other soybeans under observation were Barchet, Shanghai, Tokio, and Peking. In addition, several acres of Blackeye cowpeas grown as a field crop on the Salt River Valley Farm were studied.

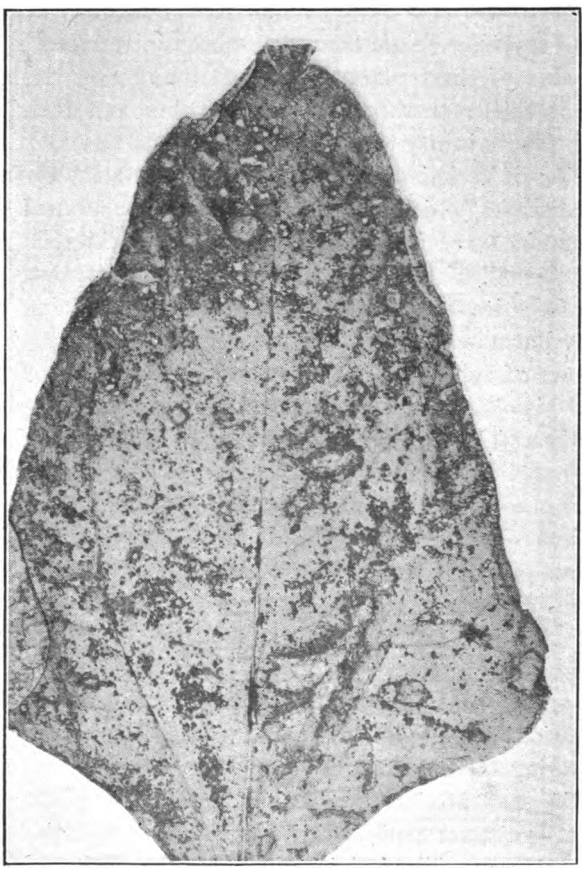

FIG. 1

Cowpea leaflet with all stages of injury. Notice sooty-black fungal growth on upper left portion.

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SYMPTOMS OF THE DISEASE

The foliage of both cowpeas and soybeans shows, as the first indication of injury, very small, brick-red spots on the upper surface of the leaves, which are confined to the areas between the veins. In severe cases, the brick-red color spreads over the veins or follows along them longitudinally. The size and color of the spots depend on the rapidity of their development and whether or not there is coalescence. On the lower surface of the leaf the spots appear at first as a red discoloration, directly under those on the upper surface. Many spots, after increasing to a diameter of four millimeters, have a brownish center and often crack open, which results in a rapid drying of the tissues and in the appearance of a dead area on the under surface of the leaf. This dead area resembles that on the upper surface of the leaf, except that it lacks the brown center. Spots larger than four millimeters in diameter have brown centers on both surfaces of the leaf, and sometimes a sooty-black fungal growth is present on the larger spots. In a dried leaf all spots are elevated, and when there is a brown center, it resembles a sunken crater. The leaf surface included in the spots may be so large that the leaf is easily broken and torn by wind. The older plants, especially Virginia soybeans, have a weather-beaten appearance due to the lack of healthy foliage.

Spots on the petioles and stems are elongated, brick-red, and also are invaded by the sooty-black fungus. In the absence of the fungus they might be mistaken for bacterial spots when compared with the spots on old bean stems.

Diseased spots on the pods of cowpeas have not been observed, but they are plentiful on the Virginia soybean and have been found on the other varieties of soybeans named, except the Biloxi. These spots are brown, cover a large area, and have present the fungal growth. Pubescense and the natural brown color of the pods render the spots less noticeable here than those on the foliage.

HISTOLOGY

Many serial sections of both naturally and artificially diseased parts were mounted for microscopic study. In these the region of disorder is most striking in the center of a spot. In passing from the margin of a spot to its center, the tissues show a gradual change from normal to plasmolyzed cells, then to a shrivelled and finally to a broken-down con-

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dition. Hyphae of *Alternaria* are numerous in the center, and they may extend a short distance into the normal cells. There is a slightly greater degree of plasmolysis in the cells of the palisade tissue than in those of the spongy tissue located at the same distance from the margin of a spot. The fungus is chiefly saprophytic in habit, but the occurrence of a few hyphae in living cells indicates a parasitic tendency.

CULTURES

About one hundred pieces of diseased leaves, petioles, stems, and pods of cowpeas and soybeans were used for cultural purposes. The pieces were first surface-sterilized by dipping into 95 percent alcohol, then immersing in 1:1000 mercuric chloride solution for one minute, after which they were placed on agar slants. Dilution cultures were poured into Petri dishes and all organisms isolated in pure cultures. The predominant organism which was found on the culture media in the test tubes and which also appeared on the surface of the diseased parts as a sooty-black fungal growth, was a species of *Alternaria.* This was accompanied by a species of *Penicillium,* and bacteria also were present in a few cultures. All these organisms were isolated and used in inoculation experiments.

INOCULATIONS

All inoculation work was done on Blackeye cowpeas and Virginia soybeans in the greenhouse of the Experiment Station in Tucson. The plants inoculated were six inches to a foot in height, except the cowpeas which attained a height of two feet and bore pods. In making inoculations, the needle-puncture water-suspension method was followed with some of the plants; other plants were sprayed over their entire surface with a water suspension and then the leaves and stems were rubbed between the fingers of the investigator in order to insure closer contact between the plant surface and the water films. A third method tried was the artificial sunburning of areas of varying sizes by means of a reading lens. After observation, these artificially sunburned areas were inoculated with *Alternaria* spores carried on a sterilized platinum loop. Since the bacteria and the *Penicillium* species isolated in cultures of cowpea and soybean leaves failed to develop on all previous inoculations, they were not tried on the artificially burned spots. Some of the inoculated plants were placed under bell jars, but the greater number were exposed to the air of the greenhouse. For comparison, aphids

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were allowed to infest both healthy and inoculated plants, and the resulting injury to the leaves and stems was studied. Plants spotted by the activities of the aphids were afterward sprayed with a water suspension of *Alternaria* spores.

The results of the treatments and the inoculations previously described appear to be conclusive. Mechanical injury by burning and by needle punctures produced the characteristic brick-red spots, and aphid injury resulted in areas identical in appearance. Sunburn by means of the lens, when the rays were partly concentrated, caused brick-red spots like the smaller ones observed in the open; stronger concentration produced sunburned areas with brown centers like the large spots seen in the field. Inoculations with *Alternaria* spores resulted in the infection of sunburned areas, both in the air of the greenhouse and under bell jars; also in the infection of needle punctures and spots showing aphid injury; the bacterial inoculations and those made from the *Penicillium* cultures failed in every case.

From these results it appears that the spotting of the leaves of soybeans and cowpeas is primarily caused either by sunburn or by aphid injury. The fungal infection is secondary and is due to a species of *Alternaria.*

DESCRIPTION OF FUNGUS

Growth profuse, sooty-black, restricted to spots on both surfaces of the leaf; conidiophores erect, solitary or grouped, one to several from a single hypha, light brown, commonly 4-septate, 47μ—81.2μ by 6.2μ—9.4μ; mycelial cells 3.5μ—4.9μ in diameter when measured in leaf sections, larger on the surface, with much variation in length; conidia clavate, obovate to club-shaped, dark brown, solitary or in chains of 2 to 6 with 1-2 hyaline cells in isthmus, 5-11 transverse septa, 0-2 longitudinal septa, 38μ—119μ by 15.6μ—25μ. This species appears to be undescribed. The name *Alternaria atrans* is provisionally suggested for it.

SUSCEPTIBILITY

Of the varieties under observation, the Virginia soybean is most susceptible to sunburn, aphid injury, and fungal infection; the Biloxi soybean is most resistant; none is absolutely immune. The degree of injury appears to be related to the time of planting and it probably varies somewhat from year to year. On July 1, 1921, the first two

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plots of Virginia soybeans, which had been planted three and three and one-half months respectively, were severely affected. All plots were diseased on October 9, but only three leaves were burned on the plants of the last planting, and no fungal growth was found. At this time aphids were beginning to congregate on a few leaves of plants of the last planting. Blackeye cowpeas had very few spots in 1921, but were badly diseased during the two previous years.

DISCUSSION

The loss of foliage to the plant is the chief damage resulting from sunburn, aphid injury, and fungal infection. Because of this loss, Virginia soybeans grown in southern Arizona as a green manure crop probably will not produce enough vegetation to compare favorably with the growth of other similar plants that are better adapted to our climatic conditions. Healthy plants of Virginia soybeans are medium in height, and leafy—characters which in themselves make this variety desirable for green manure and cover crops, but since they are affected with this disease every year with a resultant heavy loss of foliage, they may prove unprofitable as a green manure crop. The main loss with the Blackeye cowpeas is in the quality of forage, with possibly a reduced seed yield, because of the devitalized condition of the plants.

SUMMARY

1. Otootan, Biloxi, Virginia, Barchet, Shanghai, Tokio, and Peking soybeans and Blackeye cowpeas in southern Arizona are injured in varying degree in summer by sunburn and aphid injury followed by infection with a species of *Alternaria*.

2. The symptoms of sunburn and aphid injury are similar, namely, the appearance of brick-red spots which enlarge, become brown in the center, and later are often covered with a sooty-black growth of *Alternaria*.

3. The *Alternaria* species is weakly parasitic. It grows in needle puncture inoculations in healthy plants and in leaves punctured by aphids; also in sunburned areas. The species appears to be undescribed, and for it the name *Alternaria atrans* is proposed.

4. Loss of leaves is greatest in the Virginia soybean and in this variety it is extensive enough to seriously lessen the value of the plant for green manure, cover, and forage. Biloxi soybeans are the most resistant of the varieties studied.

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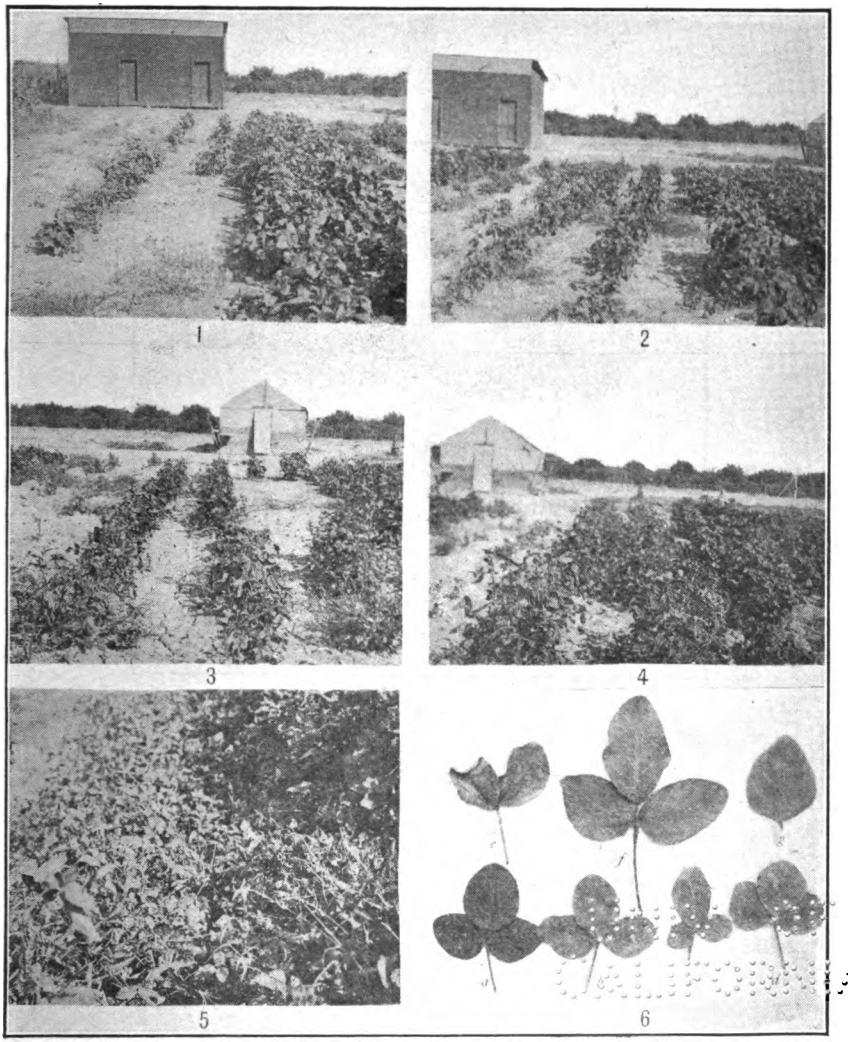

PLATE I

Figs. 1, 2, 3, 4 with Virginia soybeans at left and Biloxi variety at right. Photographed September 9, 1921.

Fig. 5.—Close view of Virginia soybeans showing unhealthy condition of leaves and drooping state of plants.

Fig. 6.—a, b, c, d, e. Progressive stages of aphid injury on Virginia soybean leaves. f. Peking soybean leaf with many aphids and slightly spotted at margins. g. Natural discoloration due to age of tissue between veins of primary leaflet.

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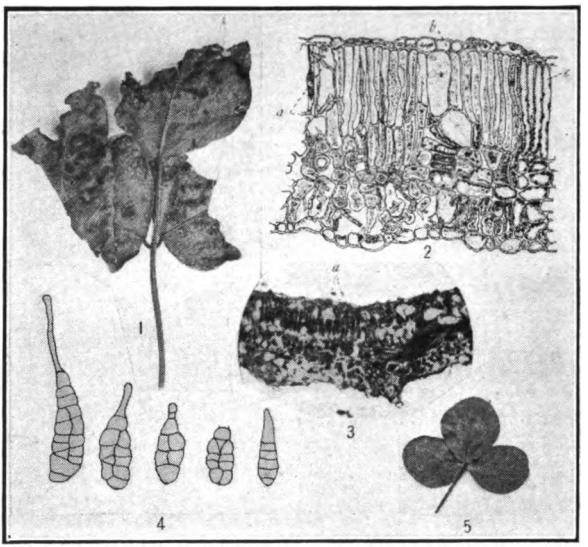

PLATE II

Fig. 1.—Soybean leaf with fungal growth in dark patches × ⅓.
Fig. 2.—Soybean leaf section at edge of a spot. a. Mycelium of fungus; b. Plasmolized cells; c. Normal cells. (Camera-lucida drawing × 100.)
Fig. 3.—Section of leaf with all cells dead in center of spot. a.—Spores on surface of leaf section. (Photomicrograph × 66.)
Fig. 4.—Typical *Alternaria* spores from leaf spots. (Camera-lucida drawing × 223.)
Fig. 5.—Virginia soybean leaf inoculated with *Alternaria* spores after sunburn.

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The University of Arizona
COLLEGE OF AGRICULTURE
Agricultural Experiment Station
Technical Bulletin No. 3

DISTRIBUTION OF ARIZONA WILD COTTON

(*THURBERIA THESPESIOIDES*)

By Herbert C. Hanson
Assistant Professor of Biology
Tucson, Arizona, April 15, 1923

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DISTRIBUTION OF ARIZONA WILD COTTON

(*THURBERIA THESPESIOIDES*)

By Herbert C. Hanson
Assistant Professor of Biology, University of Arizona

Introduction

Arizona wild cotton (*Thurberia thespesioides* A. Gray) is a very important plant in Arizona because it is the native host plant of the wild cotton boll weevil (*Anthonomous grandis thurberiae*). Coad showed, in 1914, that this weevil would feed on cultivated cotton. In 1920, when cotton was grown in a number of fields along Rillito River, near Tucson, five widely separated cotton fields were found infested. Hensley, in 1921, working under the State Entomologist, found the weevil in cultivated cotton near Continental, in the Santa Cruz Valley about thirty miles south of Tucson. He also found it in cultivated cotton near Old Fort Lowell on Rillito River, east of Tucson. So it has been fully proved that the wild cotton boll weevil will infest and damage cultivated cotton. Other insects occurring on *Thurberia* may prove destructive to cultivated cotton.

In order to protect Arizona cotton fields from infestation it is necessary to have accurate and complete information concerning the distribution and abundance of the wild cotton and the weevil. When this information is available, appropriate measures, such as the establishment of cotton-free zones, eradication of wild cotton, or other measures can be taken to safeguard the cotton industry of the State. The purpose of this paper is to bring together in a clear, usable form all the information that has been gathered on the distribution of the plant. At present, this information is scattered in botanical magazines, in bulletins and reports of the United States Department of Agriculture and of the Arizona Commission of Agriculture and Horticulture, and as unpublished observations by reliable men. This paper, by presenting the available data on *Thurberia*, will serve to avoid duplication of scouting and to show what additional work on distribution is necessary in order to protect the cotton fields.

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DESCRIPTION OF ARIZONA WILD COTTON.

In 1855 Asa Gray published the botanical name and description of the Arizona wild cotton from specimens collected in Mexico. It belongs to the cotton family (*Malvaceae*), and is closely related to cotton (*Gossypium*). It is a perennial shrub or low tree, ranging from two or three feet to over ten feet high. Under favorable conditions it may grow from a seedling to a height of five to ten feet in a single season. The stems near the base in larger plants are often two to two and one-half

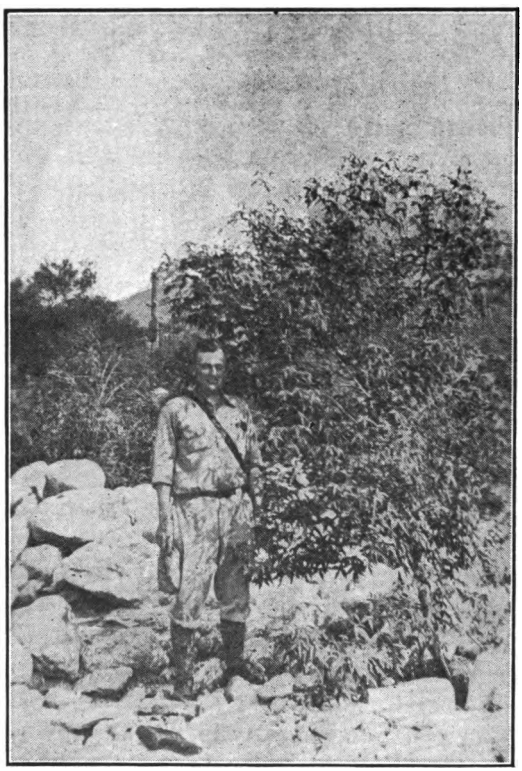

Fig. 1.—A Thurberia plant growing in a wash on the south slope of the Santa Catalina Mountains, near Tucson, Arizona. August 26, 1919.

inches in diameter. It resembles cotton in habit of growth in that there is usually one main stem with numerous lateral branches. Blooming begins usually in August and continues through September into October. The upper branches bear more flowers and fruits than the lower branches. The leaves are palmately cleft or parted into three to five parts. A large number of flower buds are produced. The flowers, usually white, but varying to pink, range from one and one-half to two and one-half inches in diameter. The plant is strikingly hand-

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some with its open growth, bright green, glossy foliage, reddish stem and attractive flowers. (See Fig. 1.) In the field it is quickly recognized against a glaring gray background of rocks and sand. (See Fig. 2.) The fruit is a small pod or boll from one-half to three-fourths of an inch in length and about one-half of an inch in diameter. It is divided usually into three chambers but, occasionally, into four or five. Each chamber contains about five dark brown, angular seeds arranged in two rows. Each seed is about five millimeters long and three to four millimeters wide. At first glance the seeds appear naked, but closer examination shows a thin coat of hairs less than a millimeter thick and closely appressed to the seed. On the inner wall of the boll, arranged along the lines where the pod breaks open, are white hairs four to five millimeters long. These hairs make the ripe, open pods resemble somewhat the cotton boll. The outside surface of the pod, the petals, sepals, flower stalks, and smaller stems are rather densely dotted with small black glands.

PREVIOUS INVESTIGATIONS.

Late in 1912, O. F. Cook, of the Bureau of Plant Industry, and Harold Bell Wright discovered the wild cotton boll weevil and its work in the capsules of wild cotton plants in the Santa Catalina Mountains, near Tucson. This discovery was described by Cook early in 1913. (4.) As early as July 4, 1903, Professor J. J. Thornber had collected the plant in Stone Cabin Canyon in the Santa Rita Mountains. In 1912 (13) he described briefly and recommended it for ornamental planting. On account of the close relationship of *Thurberia* to cotton, the United States Department of Agriculture had also paid some attention to it for three or four years previous to 1912, in connection with cotton breeding work. In August, 1913, Pierce and Morrill (10, 11) spent two weeks scouting for and examining wild cotton plants in Fish Creek Canyon, another canyon near Roosevelt, in the Santa Catalina Mountains, and in the Santa Rita Mountains. From October 19 to November 15, 1913, Vernon Bailey (1) studied the distribution, abundance, and habits of the plant in various parts of Arizona. The briefness of his survey probably accounts for some inaccurate statements, such as "naked seeds" and "sotol and blue oak are invariably with it." Schwartz and Barber (12) in a period of two months from November, 1913, to January, 1914, visited many places in Arizona studying the distribution of *Thurberia*. From April 16 to November 16, 1914, Coad (2,3) studied very carefully the biology of the weevil and the distribution and habits of the wild cotton plant throughout the Santa Catalina Mountains and on the slopes of the Tanque Verde, Rincon, and Santa Rita mountains. Townsend (14) from July 9 to October 6, 1917, travelled 1,287 miles from Las Cruces, New Mexico, southwestward into Arizona and then northwestward into the Mogollon Mountains, north of Roosevelt Lake, to determine the eastern range of the plant. In

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August and September, 1919, Herbert C. Hanson (7) spent six weeks scouting 27½ miles of washes on the southern slope of the Santa Catalina Mountains and 24 miles of washes on the western slope of the Santa Rita Mountains to determine the distribution of *Thurberia* in relation to cultivated fields. A trip was also made to the Superstition Mountains and one to Fish Creek Canyon. In September, 1920, Perry A. Glick (5) scouted the Superstition Mountains and from there northeastward to Roosevelt Lake. He also scouted the southern portion of the western slope of the Santa Rita Mountains. Hensley, in 1921, spent a few weeks scouting washes on the northwestern slope of the Santa Rita Mountains. He visited other points in the southeastern part of the State and the region around Roosevelt.

DISTRIBUTION OF THURBERIA.

Thurberia has no well defined habitat. It occurs on dry slopes, peaks of low mountains, moist beds of canyons, and in dry washes that extend from the base of mountains out through the mesa. The plants in the washes become small as the distance from the mouth of the canyon increases. The greatest

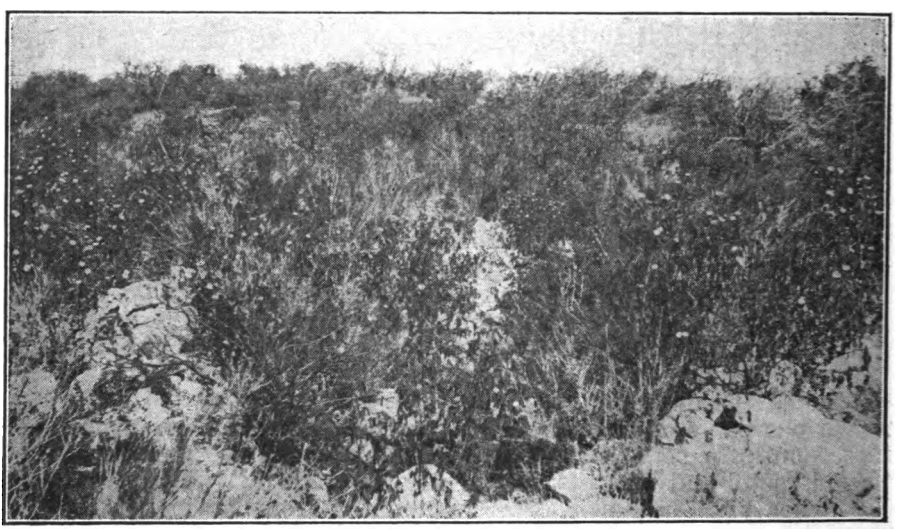

Fig. 2—Thurberia plants in full bloom growing in a wash on the west slope of the Santa Rita Mountains. September 5, 1919.

abundance of plants, according to Coad, occurs in the beds of canyons and washes. Thornber reports the largest plants, up to 14 feet high and over three inches in diameter at the base, on slopes around 4,000 to 5,000 feet. The plant ranges from about 2,200 feet to about 7,000 feet in elevation.

In Arizona the plant appears, from present data, to be most abundant in the Santa Catalina, Santa Rita, Rincon, Tanque

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Verde, and Baboquivari mountains. The most northern point of distribution is Boulder Canyon in the Bradshaw Mountains, north of Phoenix. Barber found a few plants there in 1913. Other records of the northern limits are the Superstition Mountains by Barber in 1913, the Fish Creek Canyon region and the Globe Hills north of Globe. Hensley reported finding in 1921 a few plants in a wash on the west side of Roosevelt Lake about three miles northwest of Roosevelt. In 1919 Hanson found a seedling in the bed of Tortilla Creek several miles west of Fish Creek Canyon. It appears that this seedling had grown from seed carried downstream from the group of plants on the hillside immediately west of Fish Creek Canyon, or from some other unreported group of plants further west. In the southeastern part of the State *Thurberia* has been reported from the Chiricahua Mountains and the Dos Cabezas Range in the vicinity of Bowie; from the Dragoon Mountains south of Dragoon; from the Mule Mountains near Bisbee, and from the Huachuca Mountains between Bisbee and Nogales. In the southern part of the State the western limit of distribution, from the data now collected, is the Baboquivari Mountains about 50 miles southwest of Tucson. 1921 Thompson reported *Thurberia* from the eastern slope of these mountains. In the spring of 1922, the writer found a few plants in a canyon on the west slope of Baboquivari Peak and in a wash at the extreme northwestern end of the Baboquivari Mountains. The writer also found scattered clumps of *Thurberia* on the north slope of the Coyote Mountains, which are located at the northeastern end of the Baboquivari Mountains. Table I shows in detail the regions and localities in Arizona that have been scouted and the results.

In Mexico, the plant has been reported from various localities in the mountain ranges in the eastern part of Sonora, in southwestern Chihuahua and southward to Guadalajara, Jalisco. According to Morrill (9) weevils have been collected from wild cotton at various places in western Sonora and Sinaloa.

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TABLE I. SHOWING THE REGIONS AND LOCALITIES SCOUTED, NAMES OF INVESTIGATORS, AND RESULTS CONCERNING OCCURRENCE AND ABUNDANCE.

Region or locality	Investigator	Results
Apache Mts.	Townsend	No plants found.
Baboquivari Mts.	G. E. Thompson, C. T. Vorhies	Abundant on sides of canyons on eastern slope north of Baboquivari Peak. Weevils found.
	H. C. Hanson	A few plants found in a canyon west of Baboquivari Peak and in a wash at the extreme northwestern end of the range.
Bradshaw Mts.	Barber	A few plants found. No weevils.
Cherry Creek Buttes	Townsend	No plants found.
Chiricahua Mts.	Townsend	No plants found.
	Thornber	Collected herbarium specimen.
Coyote Mts.	Hanson	Plants and weevils found on north slope.
Date Creek Mts.	Bailey	No plants found.
Davidson Spring	.....	Specimen in U. S. National Herbarium.
Dos Cabezas Mts.	Thornber	Collected herbarium specimen.
	Townsend	Two plants found in Nine-mile region. Weevils found.
Dragoon Mts..	Thornber, Bailey	Collected herbarium specimen. No plants found.
Fish Creek Canyon	Pierce, Morrill, Bailey, Barber, Hanson, Glick	Scattered plants found, especially on west-facing slope west of the canyon. No weevils found.
Globe Hills, one mile north of Globe	Townsend, Bailey	50 or more plants on south and southwest exposure of hilltop. Abundant at 3,500 to 3,800 feet.
Graham Mts.	Bailey	No plants found.
Huachuca Mts.	Goodding	Collected herbarium specimen.
Mazatzal Mts.	Townsend	No plants found during a seven-hour automobile trip along eastern side.
Mogollon Mts.	Townsend	No plants found.
Mule Mts. near Bisbee	Goodding	Collected herbarium specimen.
Pinal Mts.	Bailey	No plants found.
	Townsend	
Pinaleno Mts., western side	Townsend	No plants found.
Rincon Mts.	Thornber	Very abundant. Weevils reported from here. Collected herbarium specimen.
	Blumer	
Roosevelt Lake Region	Pierce, Morrill, Glick	No plants found in canyon near Roosevelt.
		No plants found on eastern side of lake opposite the dam, nor in six miles along Pine Creek between Roosevelt Lake and Fish Creek Canyon.
	Hensley	Reported a few plants in a wash three miles northwest of Roosevelt.
Salt River Mts.	Bailey, Pierce, Morrill	No plants found.

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Region or locality	Investigator	Results
Santa Catalina Mts.	Thornber, Coad, and others	Throughout the mountains, 2600-7000 feet, especially in beds of canyons and washes. Weevils widely distributed.
	Hanson	In washes from mouths of canyons down to about 2,250 feet; seedlings found in bed of Rillito River.
Santa Rita Mts.	Thornber, Coad, Hanson, Glick, and others	Very abundant near mouths of canyons; occurs from 2,850 feet to over 5,000 feet; only seedlings at lower elevations. Weevils common and abundant.
Sierra Ancha Mts., northern end	Townsend	No plants found.
Sierrita Mts., eastern slope	Hanson	No plants found.
Superstition Mts.	Barber,	Plants found, but very rare. No weevils.
	Hanson, Glick	No plants found.
Tanque Verde Mts.	Thornber, Coad	Plant found very abundantly. Weevils found.
Tortilla Creek on Apache Trail	Hanson	Seedling in bed of creek, several miles west of Fish Creek Canyon. No weevils.
Tortilla Mts.	Bailey	No plants found.
Tucson Mts.	Pierce, Morrill, Coad	No plants found.

DESCRIPTION AND DISTRIBUTION OF THE WILD COTTON BOLL WEEVIL.

On account of the importance of the weevil a brief description of it is here given to aid in its identification. For more complete information concerning its life-cycle and destructiveness to cotton, the bulletins by Coad and the reports by the Arizona Commission of Agriculture and Horticulture should be consulted.

The adult is a stout beetle about one-tenth to one-fourth of an inch long. The young weevils are light golden brown in color. As the weevils grow older they turn dark brown to almost black on account of the scales rubbing off. The larvae are about one-third of an inch long and white in color. They are found in the inner tissue of bud or boll.

The weevil has been reported from seven mountain ranges in Arizona; the Santa Catalina, Tanque Verde, Rincon, Santa Rita, Coyote, and Baboquivari mountains near Tucson, and the Dos Cabezas Mountains near Bowie. Further field work will undoubtedly show a greater distribution, especially in the mountains in the southwestern part of the State. All localities where *Thurberia* has been found or may be found should be thoroughly scouted for the weevil.

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Fig. 8.—Map of the southern part of Arizona showing the known distribution of Arizona wild cotton and the wild cotton boll weevil.

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Key to the names of mountains indicated by number on the map:

1. Chiricahua Mts.
2. Dos Cabezas Mts.
3. Peloncillo Mts.
4. Gila Range.
5. Pinaleno Mts.
6. Galiuro Range
7. Dragoon Mts.
8. Mule Mts.
9. Huachuca Mts.
10. Patagonia Mts.
11. Whetstone Mts.
12. Santa Rita Mts.
13. Rincon Mts.
14. Tanque Verde Mts.
15. Santa Catalina Mts.
16. Tortillita Mts.
17. Tortilla Mts.
18. Mescal Mts.
19. Pinal Mts.
20. Apache Mts.
21. Mazatzal Mts.
22. Goldfield Mts.
23. Superstition Mts.
24. McDowell Mts.
25. Phoenix Mts.
26. Salt River Mts.
27. Estrella Mts.
28. Sacaton Mts.
29. Roskruge Mts.
30. Tucson Mts.
31. Sierrita Mts.
32. Tumacacori Mts.
33. Baboquivari Mts.
34. Quitobaquita Mts.
35. Mohawk Range
36. Maricopa Mts.
37. Gila Bend Mts.
38. White Tank Mts.
39. Wickenburg Mts.
40. Bradshaw Mts.
41. Vulture Mts.
42. Trigo Mts.
43. Chocolate Mts.
44. Castle Dome Range
45. Gila Mts.
46. Coyote Mts.

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CONCLUSION.

The information concerning the distribution of *Thurberia* in Arizona is very incomplete. The only regions that have been thoroughly scouted are the Santa Catalina and the western slope of the Santa Rita mountains, and probably the Tucson, Salt Creek, and Superstition mountains. Most of the scouting has been too rapid, and too large territories were covered to secure conclusive results. Bailey, in less than a month, visited about ten different mountain ranges; Schwartz and Barber visited many places in two months, and Pierce and Morrill, in two weeks, visited four different regions. The fact that these investigators did not find the plant in some of the regions visited does not prove that it does not occur there, because the time was inadequate for thorough scouting. Coad, however, spent six months, chiefly in the Santa Catalina Mountains, securing very reliable data. Hanson and Glick concentrated their scouting on certain small areas, especially the washes on the southern slope of the Santa Catalinas and on the western slope of the Santa Ritas, and secured conclusive data.

Intensive scouting in the future will undoubtedly show a wider distribution of *Thurberia*. From a study of the map it seems likely that the plants will be found in the Pinaleno Mountains and the Galiuro Range, east of the San Pedro River. It appears that further scouting will connect the northern points of distribution with the southeastern points. The occurrence of *Thurberia* in the Superstition Mountains as reported by Barber, a very careful observer, should be checked, especially since Glick, after a fairly thorough search, failed to find it there. The occurrence of the plants in the Bradshaw Mountains, north of Phoenix, also reported by Barber, should be carefully checked also. The Goldfield, McDowell, and Estrella mountains ought to be carefully scouted on account of their nearness to the Salt River Valley. Not until 1921 was *Thurberia* reported from the Baboquivari Mountains, about fifty miles southwest of Tucson. This report brings to the fore the question of how far west it may be found. It appears that the Mohawk Range, the Gila, and Gila Bend mountains ought to be thoroughly scouted in order to determine the western limits of distribution.

In concluding, I wish to acknowledge the kindness of Professor J. J. Thornber, Director of the Arizona Agricultural Experiment Station, in furnishing numerous suggestions and data; Don C. Mote, State Entomologist of Arizona, in furnishing data and giving access to records and manuscripts of his office; Dr. C. T. Vorhies, B. R. Coad, P. A. Glick, Professor G. E. Thompson, and others, in giving data or loaning manuscripts.

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THE EFFICIENCY OF LEGUME INOCULATION FOR ARIZONA SOILS

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By R. S. Hawkins
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*THE EFFICIENCY OF LEGUME INOCULATION FOR ARIZONA SOILS

By R. S. HAWKINS, Assistant Agronomist

INTRODUCTION

A few years ago several companies handling commercial cultures of *Bacillus radicicola* began a more or less extensive advertising campaign for the sale of their products. At that time no data had been obtained as to the actual need of Arizona soils for artificial inoculation. In order to secure this data the Agronomy Department of the University of Arizona, College of Agriculture, outlined experiments in inoculation work which were carried on at the various Experiment Station farms in the State. In addition to the field work, detailed pot experiments were conducted at the University campus. The effect of inoculation was studied principally with regard to: (1) Yield; (2) increase in root growth, with its extra manurial value; (3) increase in nitrogen content of tops, roots, and of the soil in which the plants were grown.

The soils of the arid Southwest are very different from those of other sections of the United States and as yet little is known as to bacterial action in these soils. No attempt has been made in the present study to investigate the habits of the bacteria themselves further than an effort to determine the effect of the symbiotic nitrogen-fixing *Bacillus radicicola* upon the growth and nitrogen content of the various legumes studied. The methods used and the results obtained are recorded in this publication.

FIELD TESTS

SALT RIVER VALLEY EXPERIMENT FARM

The soil upon this farm is a tight-textured clay loam soil. In the fall of 1919 ten one-acre plots were planted to hairy Peruvian alfalfa, some of the plots being planted with inoculated seed and others with seed that had received no treatment. Soil from an old alfalfa field was scattered on one of the acre plots. At no time during the year could a noticeable difference in growth be observed. The yields for the years 1920 and 1921 show that the four acres planted with untreated seed averaged 132 pounds more to the acre per cutting than did the plots which had been planted with inoculated seed.

*Presented as a thesis in partial fulfillment for the work of a master's degree.

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TABLE I. INOCULATION STUDIES ON A TEN-ACRE FIELD OF ALFALFA ON THE SALT RIVER VALLEY EXPERIMENT FARM NEAR MESA, ARIZONA.

Border Treatment No.		Yield cured hay per acre per average cutting		
		1920	1921	Average for 2 years
W57	none	1475	2056	1775
W58	none	1799	2196	1997
W59	Westrobac inoculation	1653	1760	1706
W60	Westrobac inoculation	1725	2607	2166
W61	Farmogerm inoculation	1903	2292	2097
W62	Soil transfer	1946	2385	2165
W63	Mulford inoculation	1729	2262	1995
W64	Mulford inoculation	1868	2271	2069
W65	none	2335	2850	2592
W66	none	2348	2271	2259
		Lbs.	Lbs.	Lbs.
Average of the four acres planted with untreated seed		1987	2343	2165
Average of the six acres planted with inoculated seed (Including soil transfer)		1804	2263	2033

Examinations of the roots of the alfalfa plants at several times during the season showed that nodules were present in approximately equal numbers, regardless of whether the seed had been artificially inoculated or not. Previous to the present planting of alfalfa, no legume crops had been grown on this land since the time that the University of Arizona purchased it in 1915.

TABLE II. INOCULATION STUDIES WITH COWPEAS AT THE SALT RIVER VALLEY EXPERIMENT FARM NEAR MESA, ARIZONA.

Treatment	Yield per acre, threshed seed		
	1920	1921	Average for 2 years
Farmogerm inoculation	222	105	163.5
Mulford culture inoculation	225		
Westrobac inoculation	294		
Not inoculated	165	76	120.0

There was a rank growth of stems in every case, both on the areas sown with inoculated seed and on the areas sown with untreated seed. Seed did not set in sufficient quantities on any of the borders to pay for the threshing. Red Ripper cowpeas were used for these tests.

A careful examination of the roots indicates that during the hot months of the year when cowpeas are ordinarily grown for green manuring purposes few or no nodules are developed, regardless of whether or not artificial inoculation has been used.

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This same observation has been made with soybeans; namely, that nodules common to the roots of all legumes and necessary to these plants in order for them to utilize the atmospheric nitrogen through the agency of the *Bacillus radicicola,* are not present in quantity during the middle of the summer in the hot climate of the Salt River Valley.

SULPHUR SPRING VALLEY DRY-FARM

During the early part of the growing season of 1919 there was no noticeable difference between the inoculated plants and those not inoculated, in the tests conducted at the Sulphur Spring Valley Dry-Farm. Nodules were easily found on the roots of all the varieties. About fifteen days before harvest several of the inoculated plots showed gains over those not inoculated, and at harvest time they had gained 15.7 percent.

The season of 1920 was a very dry one, and all yields were so poor that comparative data were unsatisfactory. The inoculated plots made a gain of but 3.4 percent over the plots not inoculated.

Grasshoppers and rabbits injured the legume plots to such an extent during the season of 1921 that the results are not comparable.

From the data obtained and from the appearance of the plots before they were damaged by drought, insects, and rabbits during the last two seasons, indications are very strong that artificial inoculation is needed for maximum yields on this farm. The soil is a very poor clay soil with considerable sand in it. All of the legumes were grown each year on plots where no legumes had grown in previous years.

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TABLE III INOCULATION TESTS AT SULPHUR SPRING VALLEY DRY FARM.

		Yields per acre		
		1919	1920	1921
		Forage	Seed	Seed
Early Bird Velvet beans	inoc.	1375		
	not inoc.	1320		
Chinese Velvet beans	inoc.	1375		
	not inoc.	1100		
Black Eye cowpeas	inoc.	2090	88	
	not inoc.	1760	82	
Red Ripper cowpeas	inoc.	1155		451
	not inoc.	1265		407
New Era cowpeas	inoc.	2695		
	not inoc.	2475		
Mammoth Yellow soybeans	inoc.	770		
	not inoc.	770		
Pink beans	inoc.		104.5	220
	not inoc.		99	352
Red Ripper cowpeas	inoc.		71.5	
	not inoc.		71.5	
Taylor cowpeas	inoc.		38.5	
	not inoc.		44	
Groit cowpeas	inoc.			385
	not inoc.			429
Pinto beans	inoc.			102
	not inoc.			187
Tepary beans	inoc.			407
	not inoc.			517
Average gain or loss of inoculated plots		15.7%	3.4%	17.7%

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YUMA MESA FARM

In the spring of 1921 cultivation was first begun on a part of the Experiment Station Farm located on the Yuma mesa. Vetch was used as a cover and green manure crop in the young citrus orchard during the first season. Prior to planting most of the seed was inoculated with a commercial culture, but some of the seed had received no treatment. Plants from inoculated

Fig. 1.—Vetch in the citrus orchard of the Yuma Mesa Farm. Borders on left planted with inoculated seed; on right planted with untreated seed. Photograph taken April 6, 1921.

seed made a growth several times greater than did plants from seed that was not inoculated. Not only was the growth heavier, but as the season progressed many of the plants not artificially inoculated died. An examination of the roots showed that the artificially inoculated plants had developed a much heavier root system and a greater abundance of nodules than had the plants which had received no such inoculation. Practically all of the plants which survived on the area sown with untreated seed had some root nodules present, which indicates that the *Bacillus radicicola* is present to some extent in raw desert soil, but apparently in quantities not sufficient to make possible a maximum inoculation of legumes, and hence for this result artificial inoculation must be practiced.

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A mixture of vetch and rye was planted in the same orchard in the spring of 1922. A part of the area was planted with inoculated vetch seed, and the remainder with vetch seed

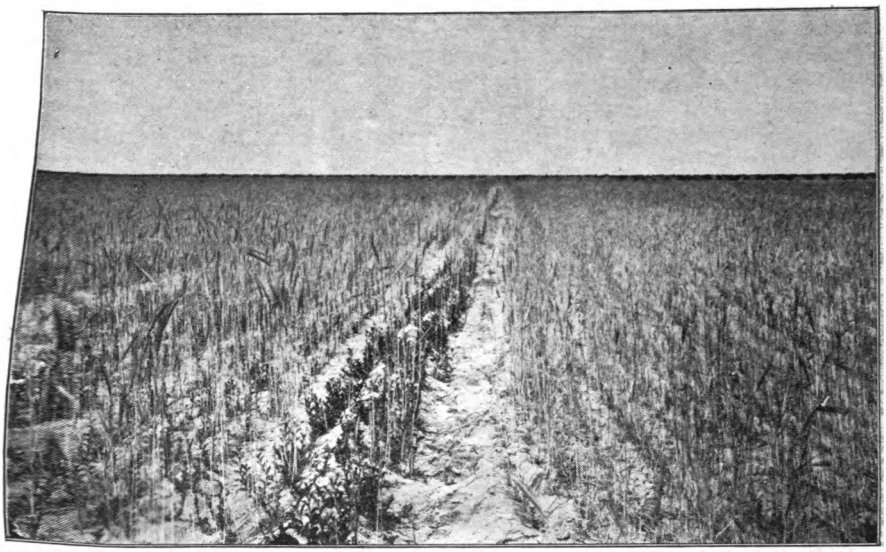

Fig. 2.—Vetch and rye on the Yuma Mesa Farm. First crop on land. Border on left planted with inoculated seed; on right planted with untreated seed. Photograph taken May 6, 1922.

not inoculated. At the present time, May 1, 1922, the growth of vetch is appreciably thicker on the area sown with inoculated seed than on the area where the seed was not inoculated, notwithstanding the fact that on both areas a heavy crop of inoculated plants had been plowed under the previous year. The soil in this orchard is uniformly sandy and contains little organic matter. One year's growth of inoculated legumes did not put the soil in condition to grow a maximum crop of vetch the next year without additional inoculation.

TABLE IV. THE EFFECT OF INOCULATION ON THE DRY WEIGHT OF THE TOPS, ROOTS, AND NODULES OF COMMON VETCH GROWN AT THE YUMA MESA FARM. AVERAGE OF FIVE REPRESENTATIVE PLANTS FROM EACH AREA. PLANTS COLLECTED MAY 6, 1922.

Soil and treatment	Dry weight in grams		
	Tops	Roots	Nodules
Cropped last year with artificially inoculated vetch.			
Inoculated this year	4.744	2.92	.173
Not inoculated this year	7.162	1.451	.286
Cropped for first time this year.			
Inoculated	4.228	1.492	.138
Not inoculated	2.283	1.01	.216

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An examination of Table 4 shows that, although the artificially inoculated plants made a much heavier root growth than those not so inoculated, the weight of the nodules on the roots of the plants not artificially inoculated was on an average greater than the weight of the nodules on the roots of the plants that had been inoculated artificially. It was also noticeable that the nodules for the most part were larger on the plants depending on natural inoculation than on those artificially inoculated. On the area cropped for the first time this year, most of the plants which were not artificially inoculated died after a few weeks. The ones which did survive had an abundance of nodules.

Data taken from these surviving plants are not strictly comparable with data obtained from the plants grown from inoculated seed, since only the best plants survived in the first instance, while average plants were used in every other case.

A marked difference in appearance can be seen between the citrus trees on the area where a good crop of green manure grown from inoculated vetch seed was plowed under last year and those on the area where green manure grown from vetch seed that had not been inoculated had been plowed under. The vetch plants from the untreated seed made little growth for green manure. The leaves of the citrus trees on the former area were dark green in color, while those of the citrus trees of the latter area were light green in color.

POT EXPERIMENTS

Pot experiments were conducted at the University campus during the growing seasons of 1921 and 1922, to determine the possibility of increasing by inoculation the yields of legumes in certain soils found in the vicinity of Tucson; and also to determine the effect of inoculation on the nitrogen content of the tops and roots of the plants and of the soil in which the plants grew. If the plants had been grown in the field it would have been exceedingly difficult to obtain fair samples of the soils for analyses.

METHODS

Three different soils were used: (1) A sandy loam virgin soil from the Rillito River bottom; (2) a similar soil that has been under cultivation with a good rotation system for a number of years; and, (3) a sandy desert soil which has never been under cultivation. These soils were all carefully screened through a one-millimeter screen and thirteen kilograms of soil were put into each pot; all the pots had been coated previously on the inside with paraffin.

Two trenches, each about a foot deep, were dug in the screen garden where the work was to be done. In the bottom of each trench a platform, having twelve holes to hold the pots, was placed in such a manner that the bottoms of the pots

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were prevented from coming in contact with the surrounding soil. Had the bottoms of the pots been placed in contact with the ground, bacteria, if present in the soil, could easily have entered through the drainage holes in the bottoms of the pots. Since the pots used were not glazed, the paraffin coating served to prevent the entrance of bacteria through the pores of the walls. After the pots containing the soils were in place on the platforms, dirt was carefully packed around them so as to fill completely the trenches above the platforms, leaving the pots protruding two or three inches above the surface of the ground. One set of twelve pots which was to be planted with inoculated seed was placed in a different section of the screen garden, approximately fifty feet from the other set which was to be planted with seed not inoculated. This was done to avoid, as far as possible, accidental inoculation.

Inoculation material was obtained from the United States Department of Agriculture, and the seed to be planted was given uniform treatment. The seed was sown on April 12, 1921, as follows:

Hairy Peruvian Alfalfa:

Virgin soil, Rillito River bottom	4 pots
Virgin soil, Rillito River bottom, sterilized*	2 pots
Cultivated Rillito River bottom soil	4 pots
Virgin desert soil	4 pots

Whippoorwill Cowpeas:

Virgin soil, Rillito River bottom	6 pots

Ito San Soybeans:

Virgin soil, Rillito River bottom	4 pots

One-half of the above pots was planted with inoculated seed and the other half with seed which had not been inoculated.

RESULTS

Notwithstanding that care commensurate with the equipment available was used to prevent accidental inoculation, some outside inoculation did occur, as is evidenced by the fact that the alfalfa plants growing in sterilized soil* from seeds which had not been inoculated, developed a few nodules on their roots. These pots of sterilized soil were used to ascertain the possible occurrence of accidental contamination, as well as for a check on the vitality of the inoculation material used. In the case of the soybeans which had not been inoculated, no root nodules could be found. In all other instances some root nodules were found on both the inoculated plants and on those not inoculated. The nodules were much more abundant, however, on the plants grown from inoculated seed than on those grown from seed that was not inoculated.

*Sterilized in autoclave for one hour at 20 pounds pressure.

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The inoculated plants reached maturity in every instance five to seven days before those that were not inoculated. All the plants of each variety were harvested at the same time and the dry weights taken. In the case of the alfalfa, three cuttings during the season were made from the pots containing the inoculated plants, and only two cuttings from the pots containing the plants which had not been inoculated, since growth after the second cutting was not sufficient to warrant harvesting. After the last cuttings were made, samples of the soils were taken and the roots were carefully washed on a screen to free them from soil particles. The same procedure was used with the soybeans and cowpeas, the cuttings being made just before the formation of the seed, with the exception of two pots of cowpeas, which were not harvested until the seed had ripened.

In every instance there was a decided gain in weight of dry matter in the tops of the inoculated plants over those not inoculated. In the case of the alfalfa this difference was greatest in the plants grown in desert soil, the gain being almost 65 percent. The next greatest gain was with the sterilized virgin river bottom soil, the gain here being 59 percent. The same soil not sterilized before planting produced plants which made a gain in weight of 55 percent, due to inoculation, while the gain in weight of the plants grown in the cultivated soil was 58 percent. This indicates that, while inoculation was of value in each case, it was of greatest value on the poorer desert soil, at least as far as gain in dry matter was concerned.

The increase in dry matter due to inoculation was more pronounced in the first cuttings in each instance, with the exception of the plants grown in the sterilized soil, where the increase was greater by 20 percent in the second cutting. This indicates that bacterial growth and action from accidental contamination was increasing in the pots which had not received inoculation. This increase was progressing at a rate that would soon render the soil in these pots more nearly like that which had been given the benefit of the inoculation. The *Bacillus radicicola* must have been present in the original soils, and when the alfalfa seed was planted and water applied the bacteria soon multiplied, and by the time the alfalfa was cut the second time they had made a large increase over the number present when the first cuttings were made. This conclusion is further substantiated by the fact that in the case of the sterilized soil, the increase due to inoculation at the first cutting was 31 percent, and at the second cutting 51 percent, while on all other soils the gain in dry weight due to inoculation averaged 62 percent at the first cutting and only 40 percent at the second cutting. While sterilization doubtless killed all of the soil bacteria present in the soil at the time, accidental inoculation did occur afterwards, as was evidenced by the pres-

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ence of root nodules on plants which did not receive the artificial inoculation. This accidental contamination was so small that the bacteria seemingly did not increase nearly as rapidly in the sterilized soil as they did in the same soil not sterilized, where bacteria were present in some quantity before any artificial inoculation was made.

Fig. 3.—Inoculated alfalfa growing in cultivated Rillito River bottom soil.

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Fig. 4.—Alfalfa plants not inoculated growing in cultivated Rillito River bottom soil.

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TABLE V. THE EFFECT OF INOCULATION ON THE DRY WEIGHT AND ON THE NITROGEN CONTENT OF THE TOPS OF ALFALFA PLANTS.

Soil	Treatment	Cutting No.	Dry Weight		Nitrogen		
			Grams per pot	Percent gain or loss	Percent	Percent gain or loss	Lbs. gain or loss per ton
Virgin Rillito River bottom	inoc.	1	11.50	54.36	2.57		
	not inoc.	1	7.45		2.33	.24	4.8
	inoc.	2	12.00		2.38		
	not inoc.	2	8.75	37.14	2.59	—.21	—4.2
	inoc.	3	1.65				
	not inoc.	3	none				
	inoc.	total	25.15				
	not inoc.	total	16.20	55.24			
Virgin Rillito River bottom sterilized	inoc.	1	9.25		2.46		
	not inoc.	1	7.05	31.20	1.99	.47	9.4
	inoc.	2	9.10		2.60		
	not inoc.	2	6.00	51.66	2.51	.09	1.8
	inoc.	3	2.4				
	not inoc.	3	none				
	inoc.	total	20.75				
	not inoc.	total	13.05	59.00			
Cultivated Rillito River bottom	inoc.	1	11.03		2.48		
	not inoc.	1	6.60	67.12	2.38	.10	2.0
	not inoc.	2	8.05		2.35		
	inoc.	2	6.05	33.05	2.40	—.05	—1.0
	inoc.	3	0.9				
	not inoc.	3	none				
	inoc.	total	19.98				
	not inoc.	total	12.65	57.85			
Virgin desert east of campus	inoc.	1	10.75		2.64		
	not inoc.	1	6.48	65.89	2.42	.22	4.4
	inoc.	2	10.20		2.68		
	not inoc.	2	6.80	50.00	2.56	.12	2.4
	inoc.	3	0.9				
	not inoc.	3	none				
	not inoc.	total	21.85				
	inoc.	total	13.28	64.53			

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The nitrogen content of the alfalfa tops was slightly greater in every instance in the first cuttings of the inoculated plants than in the corresponding cuttings of the plants not inoculated. This was also true of the second cuttings on the two soils which best responded to inoculation; namely, the desert soil and the sterilized river bottom soil. With both the virgin soil and the cultivated river bottom soils which had not been sterilized, the nitrogen content of the second cutting of plants, which had not been inoculated, was slightly higher than the nitrogen content of those plants which had been inoculated.

TABLE VI. THE EFFECT OF INOCULATION ON THE DRY WEIGHT AND ON THE NITROGEN CONTENT OF THE ROOTS OF ALFALFA PLANTS.

Soil	Treatment	Dry Weight		Nitrogen	
		Grams per pot	Percent gain or loss	Percent	Percent gain or loss
Virgin Rillito River bottom	inoc.	38.25		1.68	
	not inoc.	29.00	31.89	1.92	—.24
Virgin Rillito River bottom sterilized	inoc.	24.50		2.19	
	not inoc.	17.20	42.44	2.03	.16
Cultivated Rillito River bottom	inoc.	48.25		1.61	
	not inoc.	20.40	110.04	2.10	—.49
Virgin desert east of campus	inoc.	30.40		1.68	
	not inoc.	19.95	52.38	2.10	—.42

In every instance the dry weight of the roots of the inoculated alfalfa plants was greater than that of the plants not inoculated, this increase being less with the sterilized soil than with any of the other soils. The nitrogen content of the roots was greater in the plants not inoculated than in those inoculated, with the exception of those grown in sterilized soil, in which instance there was a gain of .16 percent in the inoculated plants over that in the plants not inoculated. This can be explained by the fact that while the third cutting or aftermath was large enough to harvest on the inoculated plants, it was not large enough on the plants not inoculated. The few leaves that did grow on the plants not inoculated were weighed and analyzed with the roots, thus raising materially the percent of nitrogen. There was practically no aftermath on the plants not inoculated which were grown on the sterile soil, and, as a consequence, the nitrogen content in this instance was lower than it was in the roots of the inoculated plants grown on sterile soil.

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TABLE VII. THE EFFECT OF INOCULATION OF ALFALFA ON THE NITROGEN CONTENT OF THE SOIL.

Soil	Treatment	NITROGEN					
		Percent at beginning	Percent at close	Percent gain or loss due to inoculation	Percent gain or loss each treatment	Grams gain or loss soil plus roots per pot	Percent gain or loss soil plus roots
Virgin Rillito River bottom	inoc.	.066	.063		—.003	.25	2.92
	not inoc.	.066	.063	none	—.003	.166	1.94
Virgin Rillito River bottom sterilized	inoc.	.066	.063		—.033	.146	1.71
	not inoc.	.066	.064	.001	—.002	.089	1.04
Cultivated Rillito River bottom	inoc.	.066	.068		.002	.949	11.06
	not inoc.	.006	.065	.003	—.001	.298	3.48
Virgin desert east of campus	inoc.	.032	.040		.008	1.55	37.27
	not inoc.	.032	.039	.001	.007	1.33	31.94

The nitrogen content of the cultivated soil of the Rillito River bottom was the same as that of the virgin soil from the Rillito River bottom at the beginning of the experiment, due, probably, to the fact that nearly all of our virgin soils are poor in humic nitrogen. A good rotation system, such as has been used on this cultivated soil, will at least keep the soil from becoming any more deficient in humic nitrogen. It is easily possible to increase the nitrogen content materially, as indicated in the last column of Table VII.

The desert soil contained a trifle less than one-half as much nitrogen at the beginning of the experiment as did the river bottom soils. The desert soil made a considerable gain in nitrogen over what it had in the beginning by growing in it either inoculated or non-inoculated alfalfa plants. This was not true with the other soils, except when inoculated alfalfa was grown in cultivated river bottom soil, in which instance it gained .002 percent. This gain would amount to 40 pounds of nitrogen per acre and does not take into consideration the nitrogen contained in the roots. When the nitrogen in the roots was added to that of the soils at the end of the experiments, all soils showed a gain in nitrogen content, with the desert soil far in the lead. The pots of this latter soil containing the inoculated

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plants made a gain of over 37 percent. In each case the gain in nitrogen of the soil and roots combined was greater with the inoculated plants.

TABLE VIII. THE EFFECT OF INOCULATION ON THE DRY WEIGHT AND ON THE NITROGEN CONTENT OF THE TOPS OF SOYBEANS AND COWPEAS.

Crop	Treatment	Dry Weight		Nitrogen		
		Grams per pot	Percent gain or loss	Percent	Percent gain or loss	Lbs. gain or loss per ton
Soybeans cut before formation of seed	inoc.	20.25		1.21		
	not inoc.	9.40	115.4	1.08	.13	2.6
Cowpeas cut before formation of seed	inoc.	38.05		2.74		
	not inoc.	15.45	146.2	1.92	.82	16.4
Cowpeas cut after formation of seed	inoc.	203.40		2.21		
	not inoc.	16.80	1110.0	2.13	.08	1.3

The results obtained with soybeans and cowpeas grown only in the virgin river bottom soil were practically the same as those of the alfalfa grown in the same soil. (See Tables 4, 5, and 6.) The principal difference was that there was a gain of .002 percent of nitrogen in the soil itself with the growing of the cowpeas, while with the alfalfa and the soybeans there was a loss of from .002 to .004, or from 40 to 80 pounds of nitrogen per acre. This loss was more than made up, in the case of the alfalfa, by the addition of the nitrogen contained in the roots, but with the soybeans there was still a loss of nitrogen in the combined roots and soil. The loss in the latter case was .72 percent in the soil growing the inoculated plants and 4.89 percent in the soil growing the plants not inoculated. The roots of the non-inoculated soybean plants had no nodules whatever, while all of the alfalfa and cowpea plants, both inoculated and non-inoculated, had nodules, the nodules being more numerous on the inoculated plants. The total gain in nitrogen when that in the roots was added to that in the soil was much greater with the cowpeas than with the alfalfa, being 8.23 percent with the inoculated cowpeas and 5.98 percent with the cowpeas not inoculated, while the gain was but 2.92 percent and 1.94 percent, respectively, with the alfalfa.

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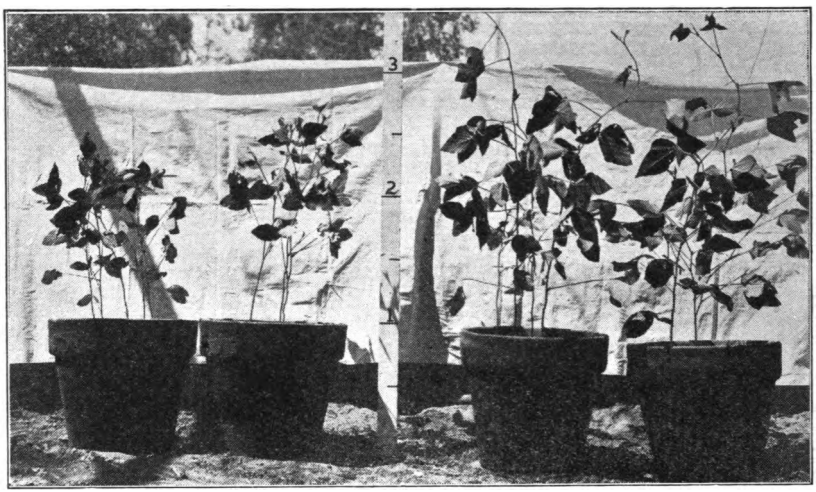

Fig. 5.—The effect of inoculation on the growth of soybeans. The plants in two pots on the right are inoculated, while those on the left are not.

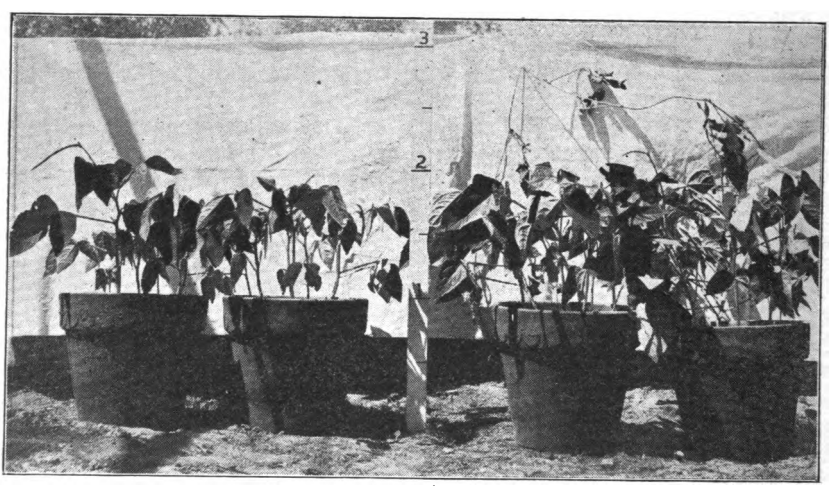

Fig. 6.—The effect of inoculation on the growth of cowpeas. The plants in two pots on the right are inoculated, while those on the left are not.

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TABLE IX. THE EFFECT OF INOCULATION ON THE DRY WEIGHT AND ON THE NITROGEN CONTENT OF THE ROOTS OF SOYBEANS AND COWPEAS.

Crop	Treatment	Dry Weight		Nitrogen	
		Grams per pot	Percent gain or loss	Percent	Percent gain or loss
Soybeans cut before formation of seed	inoc.	11.60		1.71.	
	not inoc.	8.75	32.57	1.14	.57
Cowpeas cut before formation of seed	inoc.	29.76		1.50	
	not inoc.	16.88	76.3	1.50	none
Cowpeas cut after formation of seed	inoc.	26.10*		1.41*	
	not inoc.	16.00*	57.22	.92*	.49

In every case the weight of the roots of the alfalfa was greater than the combined weights of the various cuttings of the tops of the alfalfa, averaging 60.5 percent of roots and 39.5 percent of tops. With the cowpeas the weight of the tops averaged 61 percent, while that of the roots averaged 39 percent of the total weight. The root systems of the soybeans averaged 42 percent and the tops 57.7 percent. This difference in the weights of the root systems of various legumes emphasizes the fact that in growing a crop for green manuring purposes the amount of top growth is not always the biggest factor in the matter of improving the soils.

*Roots not washed out of the soil immediately upon harvesting the cowpeas. The roots were partially decayed when finally washed and analyzed. In all other instances the roots were taken from the soil within twenty-four hours after harvesting the tops.

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TABLE X. THE EFFECT OF THE INOCULATION OF SOYBEANS AND COWPEAS ON THE NITROGEN CONTENT OF THE SOIL.

Crop	Treatment	NITROGEN						
		Percent at beginning	Percent at close	Percent gain or loss due to inoculation	Percent gain or loss each treatment	Grams gain or loss soil plus roots per pot	Percent gain or loss soil plus roots	Lbs. gain or loss per acre
Soybeans cut before formation of seed.....	inoc.	.066	.064		—.002	—.062	—.72	—9.5
	not inoc.	.066	.062	.002	—.004	—.42	—4.89	—64.4
Cowpeas cut before formation of seed.....	inoc.	.066	.068		.002	.71	8.23	108.9
	not inoc.	.066	.068	none	.002	.51	5.98	78.2
Cowpeas cut after formation of seed.....	inoc.	.066	.068		.002	.63	7.32	96.6
	not inoc.	.066	.068	none	.002	.41	4.81	62.9

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TABLE XI. THE EFFECT OF INOCULATION ON THE PERCENT OF ROOTS AND TOPS OF ALFALFA, COWPEAS, AND SOYBEANS. DRY WEIGHT.

Crop	Treatment	PERCENT	
		Tops	Roots
Alfalfa*			
Virgin soil	inoc.	39.6	60.4
Rillito River bottom	not inoc.	35.8	64.2
Virgin soil	inoc.	45.8	54.2
Rillito River bottom	not inoc.	43.1	56.9
Cultivated soil	inoc.	31.6	68.4
Rillito River bottom	not inoc.	38.3	61.7
Virgin soil	inoc.	41.9	58.1
desert east of campus	not inoc.	39.9	60.1
Cowpeas**			
Cut before formation	inoc.	56.3	43.7
of seed	not inoc.	47.8	52.2
Cut after formation	inoc.	89.7	11.3
of seed	not inoc.	50.3	49.7
Soybeans**			
Cut before formation	inoc.	63.6	36.4
of seed	not inoc.	51.8	48.2

*All cuttings of the alfalfa tops are included. In the case of the cowpeas and soybeans but one cutting was made.

**Virgin Rillito River bottom soil unsterilized was the only soil used with the cowpeas and soybeans.

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TABLE XII. THE AMOUNT OF NITROGEN TAKEN FROM THE SOIL AND THAT TAKEN FROM THE AIR FOR THE USE OF THE PLANTS.

Crop	Treatment	Grams in tops	Grams in roots	Total in plants	Grams in soil at beginning	Grams in soil at end	Loss or gain in soil	Grams taken from soil by plants	Grams taken from air by plants	Percent taken from air
Alfalfa										
Virgin soil—Rillito River bottom	inoc.	.62	.64	1.26	8.58	8.19	—.39	.39	.87	69
	not inoc.	.40	.56	.96	8.58	8.19	—.39	.39	.37	58
Virgin soil—Rillito River bottom sterilized	inoc.	.53	.54	1.07	8.58	8.19	—.39	.39	.38	54
	not inoc.	.35	.35	.70	8.58	8.32	—.26	.26	.44	63
Cultivated Rillito River bottom soil	inoc.	.48	.69	1.17	8.58	8.84	.26	none	1.43	125
	not inoc.	.30	.43	.73	8.58	8.45	—.13	.13	.60	82
Virgin desert soil	inoc.	.58	.51	1.09	4.16	5.2	1.04	none	2.13	195
	not inoc.	.33	.42	.75	4.16	5.07	.91	none	1.66	221
Cowpeas										
Cut before formation of seed	inoc.	1.04	.45	1.49	8.58	8.84	.26	none	1.75	117
	not inoc.	.30	.25	.55	8.58	8.84	.26	none	.81	147
Cut after formation of seed	inoc.	4.50	.37	4.87	8.58	8.84	.26	none	5.13	105
	not inoc.	.36	.15	.51	8.58	8.84	.26	none	.77	151
Soybeans										
Cut before formation of seed	inoc.	.25	.20	.45	8.58	8.32	—.26	.26	.19	42
	not inoc.	.10	.10	.20	8.58	8.06	—.52	.52	.00	0

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The cowpeas obtained a greater percent of nitrogen from the air than did either the alfalfa or the soybeans. In the case of the soybeans more nitrogen was obtained from the soil than from the air, the inoculated plants having obtained 42 percent from the air and the remainder from the soil. With the cultivated river bottom soil, the inoculated plants of alfalfa obtained more than enough nitrogen for their own use from the air; this was also true for both the inoculated plants and those not inoculated that were grown on desert soil. With the alfalfa the inoculated plants in all cases, except when grown on desert soil, obtained a larger percent of their nitrogen from the air than did the plants not inoculated.

TABLE XIII. THE EFFECT OF APPLYING INOCULATION MATERIAL AT DIFFERENT RATES ON THE WEIGHT IN GRAMS OF THE TOPS AND ROOTS OF ALFALFA.

Treatment	Tops	Roots	Total
Soil not sterilized			
seed not inoculated	.722	.318	1.040
*Soil sterilized			
seed not inoculated	.388	.614	1.002
seed given normal inoculation	.255	.201	.456
seed given 10 times normal inoculation	.433	.393	.826
seed given 20 times normal inoculation	.791	.700	1.491

Twelve pots containing uniform virgin Rillito River bottom soil were planted to alfalfa, the seed of which had been treated with different amounts of the inoculation material to ascertain the effect of an excess application. Nitrosoil inoculum was used for this test, but it was not as fresh as it should have been. The nodules on the roots of the alfalfa grown in the soil not sterilized were much larger as well as more numerous than those on the roots of the plants given any of the other treatments, except that in the case of the pots receiving twenty times the normal application of inoculation material, the nodules were as numerous, but were very small. The nodules resulting from action of the bacteria already in the soil were many times larger in every instance than were those resulting from action of the bacteria applied in the artificial inoculum. This has been noted in practically all of the inoculation experiments conducted by the Experiment Station during the last few years.

A study of Table 13 shows that inoculation did not increase the weight of the tops or the total plant weights with the normal application or with ten times the normal application of inoculation material, but did increase the weights with an application of twenty times the normal. These results empha-

*Sterilized in autoclave for one hour at 20 pounds pressure.

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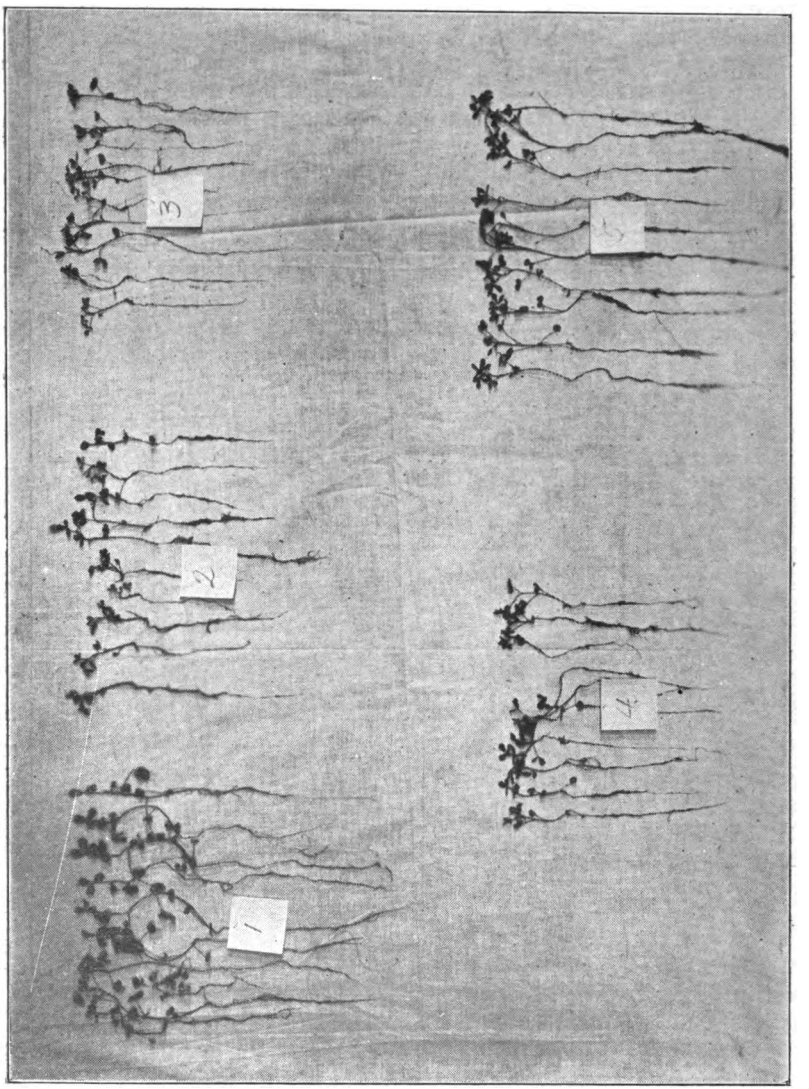

Fig. 7.—The effect of applying inoculation material at different rates. (1) Soil not sterilized, plants not inoculated; (2) soil sterilized, plants not inoculated; (3) soil sterilized, plants given normal inoculation; (4) soil sterilized, plants given 10 times normal inoculation; (5) soil sterilized, plants given 20 times normal inoculation.

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size the necessity, when making pot culture tests, of using the amount of inoculation material recommended by the companies which put out this material. The tendency is for one to use as much inoculum on a few pot cultures as is recommended by the manufacturing company for perhaps an acre, and to judge the results in the light of normal applications.

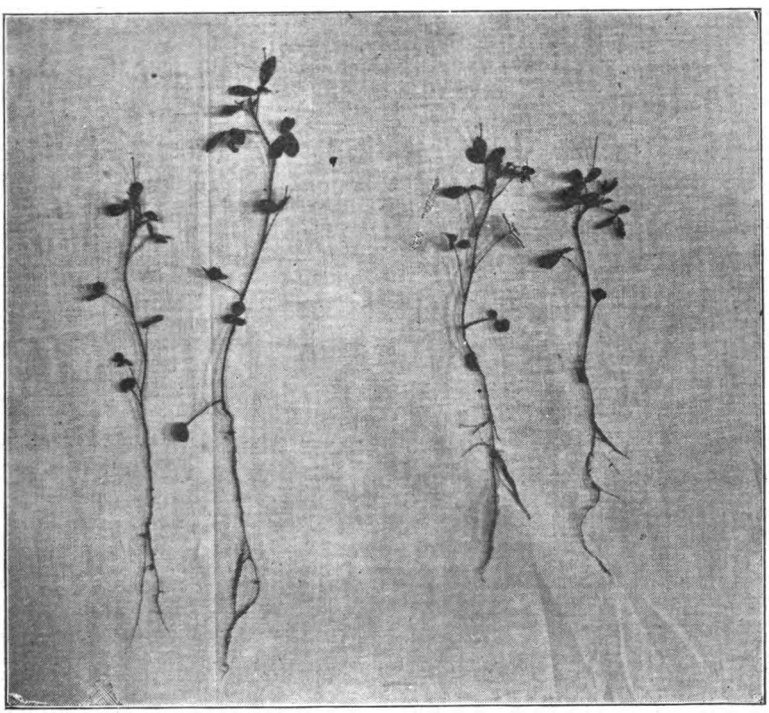

Fig. 8.—The difference between natural and artificial inoculation on the formation of root nodules. The nodules on the roots of the two plants on the left were formed through the action of bacteria already present in the soil; the nodules on the roots of the two plants at the right were formed by bacteria introduced in commercial inoculum and are too small to be seen in a photograph, in most cases being smaller than a pinhead.

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SUMMARY

Inoculation has not proved beneficial with alfalfa at the Salt River Valley Experiment Farm.

In most instances inoculation has been beneficial at the Sulphur Spring Valley Dry-Farm.

Increase in yield of vetch due to inoculation has been marked on the very sandy soil of the Yuma Mesa Farm. This increase was greater during the first year of cultivation than during the second. In soil where inoculated vetch had been grown the preceding year, the inoculation of vetch seed increased the yields very materially over vetch seed not inoculated.

The weight of nodules on the roots of the vetch plants which had not been inoculated was greater than on those which had been inoculated, while the number of nodules per plant was less.

Inoculation hastened maturity from five to seven days with alfalfa grown in pots at the University campus in the screen gardens.

The weights of the tops and of the roots of all legumes experimented with in the pot tests were increased materially by inoculation.

Inoculation increased the weight of nitrogen in the tops of the alfalfa from one to nine pounds per ton, depending on the soil used. The gain in nitrogen content of the cowpea hay was 16 pounds per ton, and but 2.6 pounds per ton with soybeans.

In poor desert soil or in Rillito River bottom soil which had been in cultivation for a number of years a distinct gain in the nitrogen content of the soil itself was obtained by growing alfalfa, either inoculated or not inoculated. With the other two soils there was a loss in nitrogen content.

When the nitrogen content of the roots was added to that of the soil, in every instance with the alfalfa there was a gain of from 1.04 percent in the case of the virgin Rillito River bottom soil to 37.27 percent with the desert soil. Cowpeas grown on the virgin soil of the Rillito River bottom gained from 6 to 8 percent nitrogen, while soybeans incurred a loss of .72 to 4.89 percent.

Inoculation increased the percent of roots to tops with alfalfa, but had the opposite effect with cowpeas and soybeans.

Nodules produced on the roots of vetch and alfalfa plants by the action of bacteria already present in the soil, are as a rule larger than those produced by the bacteria in commercial cultures.

Root nodules cannot be found in nearly so great abundance during the hot summer months as during cooler weather.

An application twenty times normal of commercial inoculum in sterile soil gave a yield of alfalfa three times as heavy as a normal application.

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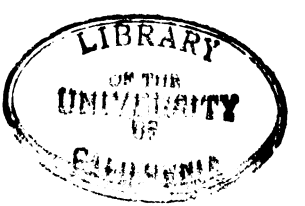
PHYSICAL AND CHEMICAL FACTORS IN THE GROWTH OF ASPARAGUS

By Earl B. Working

Presented as a thesis in partial fulfillment for the degree of Doctor of Philosophy at the University of Arizona.



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EARL B. WORKING.

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PHYSICAL AND CHEMICAL FACTORS IN THE GROWTH OF ASPARAGUS

By Earl B. Working

INTRODUCTION

This work was planned primarily as a study of the physico-chemical basis of growth. Asparagus furnishes a good subject for the study of the growth of plant tissue because of the comparatively large volume of the young shoots and their tolerance of mechanical injury. It must be remembered that in the growth of both the young shoots and the seedlings we have to do primarily with growth from storage (57), while photosynthesis gradually increases in importance as the chlorophyll-bearing surface increases.

REVIEW OF MATERIAL

PUBLICATIONS

There are numerous publications on the culture and fertilization of asparagus (1, 3, 8, 11, 23, 40, 41, 62, 64), but only those which seemed to add something of information are included in the bibliography.

A light sandy soil is generally recommended as giving the best results, sometimes with the provision that there should be a liberal supply of humus. Where commercial fertilizers were used, the best results in nearly all cases were obtained by the application of a complete fertilizer, supplying nitrate, phosphate, and potash, although the soils at the different stations varied widely. Where different potash salts were tried, KCl invariably gave the best results, while K_2SO_4 and wood ashes were of considerably less value.

The widest divergence of opinion seems to occur with regard to the value of applying NaCl. Older writings very generally advise liberal use of it. H. C. Thompson (33) recommends that where either KCl or kainit is used, salt is not necessary; that otherwise 300 to 400 pounds

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per acre may be beneficial. It would be natural to assume that where $NaNO_3$ and KCl are being used no further addition of Na or Cl ions should be necessary. For home beds it is argued that the application of salt is beneficial as a method of inhibiting the growth of weeds.

Morse (23) mentions a large absorption of SO_4 ions, but states that a sufficient supply seems to be obtained from the acid phosphate used.

Chemical studies of the asparagus plant are less numerous (19, 40, 54, 63, 68), but the work of Morse (40) is comprehensive. His analyses of young stalks taken at different times during the cutting season show a progressive change in some of the constituents, particularly in sugars and non-protein nitrogen. The nitrogen decreases, but sugars increase notably, a fact which he correlates with a somewhat slower growth and increased photosynthesis. During the cutting season the roots are shown to have lost a large amount of sugar; more than twice what would have been necessary to produce all the carbonaceous matter in the crop. On the other hand no loss in nitrogen was observed, and ash, fiber, and lignin increased in percentage. K, Na. and P_2O_5 seem to be lost by the roots in approximately the same quantity in which they are found in the stalks. Analyses of the tops in summer and fall show a loss in protein and sugar, and in K, Mg, and P_2O_5. The author expresses the opinion that this is chiefly a translocation back to the roots, with the possibility that a considerable portion may go to the berries. The physiological need of the asparagus plant for water is stressed, with the suggestion that irrigation might often be of value, owing to the sandy quality of most asparagus soils.

MacDougal (29) describes the effects of etiolation on asparagus, and in a recent publication (31, p. 96) gives the results of swelling sections of asparagus stalks under the auxograph.

Büchner (9) made daily measurements of the length of asparagus stalks over periods of from 18 to 24 days, and also measured the length of the growing region. His tables include total growth in the period of observation, maximum growth in one day, mean daily growth, mean length of the growing region, "mean maximum growth rate in the most rapidly growing region," "mean maximum growth rate," and mean growth rate. However, there are errors in the mean growth rates, including a uniform misplacement of the decimal point. This is the only result for which all the necessary data are given.

COMMERCIAL PRACTICES

Asparagus is cultivated to a greater or less extent in nearly all sections of the United States, and in most of them is found wild as an escape. It grows in nearly all types of soil, survives a very large amount of alkali, and grows even in brackish swamps. In dry regions it is found along

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ditch banks and creeks, and in other locations where the water supply is sufficient.

Conditions for successful commercial culture, however, are much more restricted. An ample water supply is of great importance; the preferred soil is of light texture, usually sandy, and with a good supply of humus—a so-called "early" soil. In regions where the soil has been cropped for a long time, as in sections of Massachusetts and New Jersey, commercial fertilizers are often used.

Probably the largest fields in the world are found on the islands of the Sacramento River. Normally these islands are swampy or even flooded at times of high water, so dikes have been built around them and drainage canals cut across at intervals. During the wet season water is pumped out from these canals into the river, and during the dry season river water is pumped into the canals for irrigation purposes.

Here the preferred soil is what is known as "ash" soil, dark in color, and consisting of large quantities of peat mixed with river sediment. The "sediment" soils of the region are usually higher, where peat formation has not occurred, and are clayey and rather heavy. Asparagus fields in this type of soil are slower to come into bearing and seem to be somewhat more sensitive to insect attacks, particularly those of the so-called "centipede". They are said to continue a high rate of production for a greater number of years than in ash soils. The crop is produced a little later in the season.

Mr. A. C. Harvie, manager of Ryer Island, states that under approximately equivalent conditions of cultivation the profitable life of a field in sediment soil is 15 to 18 years, and in ash soil 12 to 15 years, while at some distance lower on the river, where diffusion from San Francisco Bay brings the total salts in the river water up to 26 parts per 10,000, the life is only 6 to 10 years. In particularly dry years this diffusion may be noticed as far up as Ryer Island, and irrigation is stopped there if the total salts reach 18 parts per 10,000, because of the fear that they may be injurious. Of course the length of life of an asparagus field is not necessarily an accurate criterion of the suitability of the soil in which it is growing because of the wide divergence of opinion as to the time at which it would be more profitable to plow it up and replant, and because the amount of cultivation makes a very great difference in the condition and productive life of the plants.

EXPERIMENTAL WORK

INTRODUCTION

Terms.—As is the case with many other biological terms, the exact limits of the connotation of "growth" are difficult to define. On the one hand there are various instances of undisputed growth with no increase

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in dry weight (12, 49), while on the other hand such pathological conditions as edema could scarcely be considered as growth by any stretch of the imagination. While doubtful cases are not likely to be found in this study, it should be emphasized that the time of maximum growth, as determined by a criterion such as length, volume, or living weight, will by no means necessarily coincide with the time of the maximum increase of dry matter.

Throughout this paper, unless specific exception is made, increase in length of the main stalk will be taken as the criterion of the growth of asparagus. Aside from the fact that it leaves root growth out of consideration, this method is evidently in error from two standpoints; first, in that it takes no account of changes in the constitution and composition of the stalk; and, second, in that it does not account for lateral growth. Measurements of the increase in diameter of the young shoot have been included, but no detailed measurements were made of the growth of lateral branches, as the chief interest is in the young shoot before it has branched.

Methods.—Four methods were used to measure growth in length.

(1) For some purposes the distance from the surface of the soil to the tip of the stalk was measured with a millimeter scale at suitable intervals of time.

(2) To determine whether there might be minute variations in the rate of growth, the horizontal microscope was used, being focused on the tip of the stalk. With this method it is important that the light be uniform on all sides in order to avoid phototropic curvatures.

(3) A very useful method is that of drawing fine horizontal lines with India ink at 5 or 10 mm. intervals on the stalk, thus indicating exactly the region in which the growth is taking place.

(4) Probably the most valuable of all is the auxographic method because it gives continuous records without the necessity of constant attention.

In the first attempts to use the auxograph on asparagus, a cork was made to bear on the tip of a young shoot. While some satisfactory records were obtained by this method, most of the records were spoiled on account of curvatures of the stalk, apparently due to thigmotropism, possibly in part to phototropism. The most satisfactory method of attachment found was by means of a loop in the end of a No. 36 insulated copper magnet wire suspended from the end of a simple lever auxograph. This seemed to cause no injury in any case, and yet the wire had sufficient stiffness to allow the loop to be placed very close to the tip of the stalk without slipping off. As will be shown, the growth rate at the extreme tip is comparatively slow, so that the error introduced is slight. To avoid breaks in the records of rapidly growing shoots, a special lever set

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was constructed to reduce the pen movement to one-half the amount of growth.

Some special methods for other purposes will be described where the measurements are discussed. Measurements of the diameter of stalks were made with a vernier caliper at 15 mm. from the surface of the soil, after longitudinal growth at that point had ceased. After elongation has stopped, there is only a very slight increase in diameter.

For most of the temperature records, mercury thermometers were used with their bulbs thrust into the soil to a depth of 1 cm. During some of the measurements, air temperatures were taken with a mercury thermometer, and for a short period a thermograph was used to record accurately the times of significant temperature changes. Temperatures of the stalks and fine branches were taken by means of a thermocouple according to the method of Shreve (56).[1]

Materials—The Possibility of Comparable Results.—All seeds used were from a single lot of the Palmetto variety, obtained from the Burton Seed Company. The roots were especially selected 2-year roots of the Washington strain, obtained from E. W. Jamison of Ontario, California. They were kept in cold storage until wanted for use in the experiments. Morse (40) shows that there is a variation in the composition of stalks cut at different periods during the growing season. As the greatest variations which he finds are in sugars, the results of the determinations given in Table I are believed to indicate that stalks are comparable in composition if taken from roots that have been forced for approximately

TABLE I.—THE SUGAR CONTENT OF ASPARAGUS SHOOTS FROM ROOTS FORCED FOR DIFFERENT LENGTHS OF TIME.

	Percent Total Sugars in Stalks				
	Jan. 13	Jan. 30	Feb. 17	Mar. 1	Mar. 7
Roots removed from storage Jan. 6	8.7	14.8			
Roots removed from storage Jan. 25		10.1	15.6		
Roots removed from storage Feb. 9			9.6		15.1
Roots removed from storage Feb. 21				9.8	

[1]When first used, the Leeds and Northrup portable galvanometer with which the thermocouple currents were measured gave very erratic readings, due to variations in resistance at the sliding contact which forms the only connection with the upper end of the phosphor-bronze suspension ribbon. This was bridged by soldering one end of an insulated copper wire to the upper support of the suspension ribbon and the other end to the binding-post on the outside. No further trouble was experienced. As it was used, this method is thought to be accurate to 0.1 or 0.2 degrees; even this is greater accuracy than is necessary, considering the rapid changes in the temperatures measured.

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the same length of time. Where results were to be compared, care was taken that the roots were thus comparable.

THE EFFECT OF LIGHT ON GROWTH

General Observations.—The effect of light on growth has attracted the interest of plant physiologists from very early times (29). The great

Fig. 1—The effect of illumination from one side and above on an asparagus plant.

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obstacle to its exact determination is the difficulty of keeping all other factors, such as temperature, humidity, and air movement, equivalent in both the dark and the illuminated cultures. Added to this is the possible effect of the very slight exposure to light necessary for observations (29, p. 53). Individual differences of the illuminated and etiolated specimens offer special difficulties in auxographic work, because of the impossibility of simultaneously measuring large numbers of individuals in order to obtain averages with a low probable error.

When the temperature was kept between 17° and 21°C., shoots grown in the dark at the Desert Laboratory in 1921 and 1922 acted very much as the specimens reported by MacDougal (29, p. 73) with the possible exception of a less exaggerated stem diameter. Branching became profuse when the temperature remained near the higher limit, but even at considerably higher temperatures secondary branching was absent or greatly reduced. Staminate flowers were produced in profusion.

The Effect on Branching.—To learn whether etiolation would retard branching at high temperatures, parallel cultures were carried on in the glass house at temperatures sometimes falling as low as 15°C., at night, but rising to 30° to 40°C., during the day. A portable dark chamber was prepared so that it could be taken into a very dim light for observations. A slow current of air was passed in through a light trap, keeping the temperature and humidity practically identical with those outside. Three crowns were set in each culture, being selected in pairs that were as nearly as possible alike in weight, length of roots, and general appearance. Each of the first four shoots in the dark chamber broke ground on the same day as one in the light, thus affording a very close comparison. The growth rates in the two cultures were almost identical, the slight variations seeming to be nearly equally distributed between the two cultures. Table II gives the observations, and does not show any appreciable light effect on primary branching. After the fifth day in each case the shoots reached the top of the dark chamber and readings were discontinued. Number 6 had already reached the top on the fifth day, but it is hardly probable that sufficient reaction had occurred to vitiate the observations for that day.

Figure 1 illustrates a pot of asparagus grown near an east window at the Desert Laboratory, with no other source of light. A very strong initial phototropism is shown. The more nearly vertical growth later may be due largely to the greater amount of light from above after the stalk had come nearer to the window, thus reducing the light effect sufficiently that geotropism became the dominant factor. In any case, the much greater development of the branches on the illuminated side is noteworthy, and would show that the growth of asparagus is not retarded by light of the intensity present there.

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TABLE II.—THE RATE OF GROWTH OF ASPARAGUS IN LIGHT AND IN DARKNESS.

Object No.	Illumination	Date of appearance of shoot.	3rd Day			4th Day		5th Day	
			Diam. of shoot at base.	Length of shoot.	Mean length of branches.	Length of shoot.	Mean length of branches.	Length of shoot.	Mean length of branches.
			mm.	mm.	mm.	mm.	mm.	mm.	mm.
1	light	Mar. 27	4.5	72	1.0	155	7	348	19
2	dark		4.7	69	.8	153	6	351	19
3	light	Mar. 28	3.9	83	1.2	161	8	362	21
4	dark		3.1	71	1.5	138	12	331	30
5	light	Mar. 30	4.3	75	.7	163	4	381	22
6	dark		5.0	81	.5	179	2.5	417	17
7	light	Apr. 5	2.9	58	.8	129	7	263	14
8	dark		3.0	62	1.0	134	7.2	270	14.5

The Effect on Root Growth.—Of great interest was the failure of completely etiolated plants to produce many fibrous feeder-roots, while in the illuminated cultures the pots soon became filled with such roots. In two illuminated pots where no shoots were allowed to grow higher than 8 or 10 centimeters there were few fibrous roots, but the comparatively short duration of the experiment (3 weeks) would make it inadvisable to draw conclusions from it. Considering the great food reserves in the storage roots, the failure to produce fibrous roots can scarcely be due to any lack of food material, but at present it would be mere theorizing to attempt to say whether the effect is due to the presence of some growth-promoting or growth-inhibiting substance in one case and to its absence in the other, or merely to a change in the carbohydrate gradient when photosynthesis has reached a great enough rate.

The Effect on Growth Rate.—The only instance observed of any effect of light on growth rate during the early or middle life of the shoot was under conditions such as were present in the case of Fig. 1. As no such effect is shown in Table II, the most reasonable explanation at hand is that the same factors which cause the change to more nearly vertical growth, presumably a geotropic curvature, retard the starting or early growth of the branches at the same time that they reduce the growth rate of that side of the stalk. Auxographic tracings of plants grown in the light do not show any variations traceable to the change from day to

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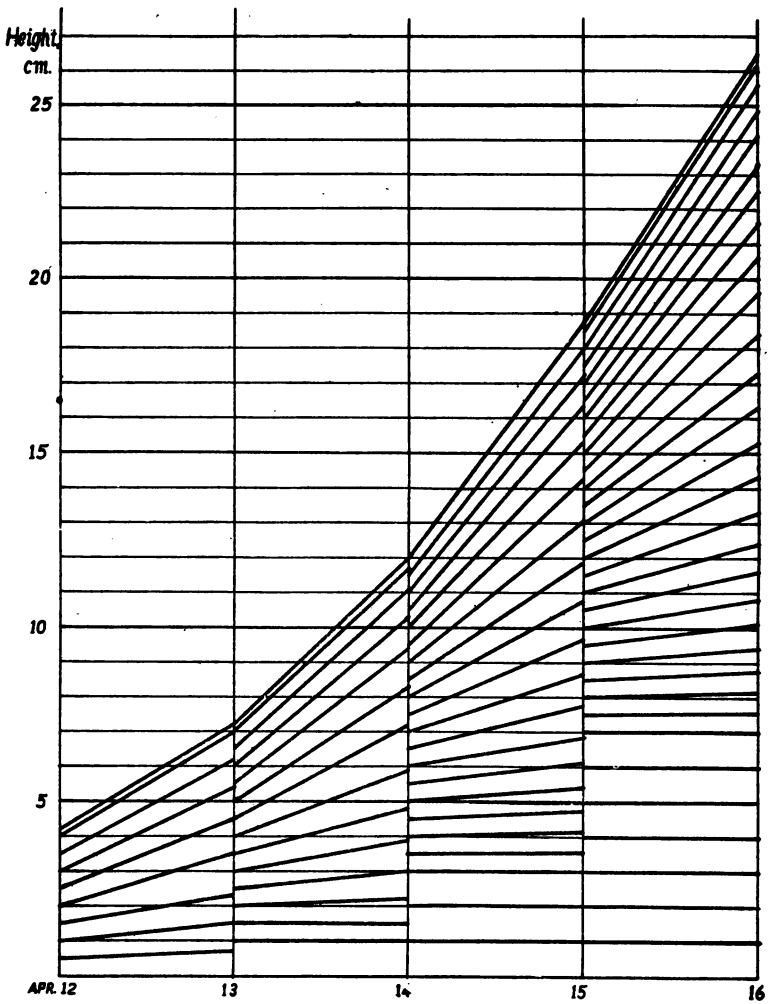

Fig. 2—Amount of growth and distribution of the growing region of a young asparagus shoot, marked daily into 5 mm. divisions.

night or vice-versa. On the other hand, both seedlings and shoots from storage roots finally attain a greater height when etiolated, apparently due to a prolongation of the growing period. Towards the tip of the stalk the internodes become considerably longer in the etiolated specimens than in green ones. Lack of secondary branching is especially noticeable in etiolation, either of the seedlings or the shoots.

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The Effect on Acidity.—Hydrogen ion determinations on the expressed juice of etiolated shoots by the colormetric method of Clark (10), modified by Duggar (13), varied between PH 5.4 and PH 5.8, with 5.6 as a mean. PH 5.6 was also the mean of measurements on normal green shoots, whether they were cut early in the morning or late in the day. Titrations against NaOH with phenolphthalein as indicator gave as mean values 10 cc. of juice of etiolated shoots = 2.0 cc. N/10 HCl, and 10 cc. of juice of normal shoots = 2.8 cc. N/10 HCl. It will thus be seen that there is no such radical change in acidity as is shown in various succulent plants (20; 58, p. 68).

THE EFFECT OF TEMPERATURE ON GROWTH

Temperature Observations.—The great influence of temperature upon plant growth is a matter of common knowledge. The effects of tempera-

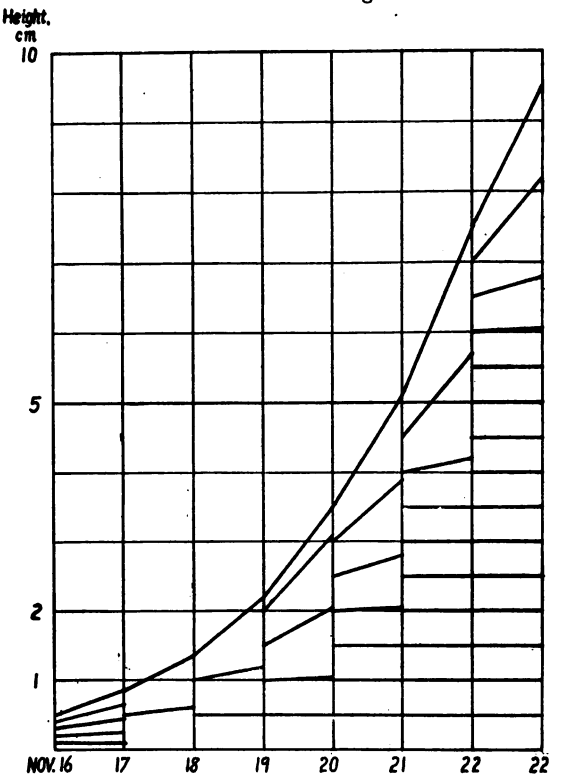

Fig. 3—Amount of growth and distribution of the growing region of a young asparagus seedling, marked daily into 5 mm. divisions (first day in 1 mm. divisions).

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ture extremes (38, 50, 53) are interesting, but the retardation of metabolic processes in the roots by cold storage is the only one of special value to this study.

The temperatures of prime interest in a study of growth are those of the absorbing organs, the storage tissue, the conducting tissue, the synthesizing region, and the growing region. In asparagus the absorbing organs (fibrous roots) and the storage tissue (seeds or storage roots) will not differ appreciably in temperature from the immediately surrounding soil. The soil temperature will vary with the air temperature, but with considerable lag, and with the additional effect of evaporation and sometimes the heat from direct illumination.

The measurements recorded in Table III indicate that the temperatures of the conducting tissue and growing region do not vary widely from the air temperatures, but average a little lower, due to transpiration. Even direct sunlight does not show the great effect found with xerophytic plants (2, 39, 50). In each case the air temperature is the mean of readings taken adjacent to the asparagus stalk, immediately before and after reading the asparagus temperature; the thermocouple was always shaded. The soil temperatures were taken with a mercury thermometer with the bulb 1 cm. below the surface.

TABLE III.—SURFACE TEMPERATURES OF ASPARAGUS STALKS

Time	Subject	Soil temp.	Air temp.	Asparagus temp.
Mar. 17, 1921 10:30 A.M.	Young shoots, growing region, shade near base	16.7	22.1	20.8
			22.4	20.9
			21.3	20.0
	Mature stalk, fine branches		21.8	21.1
			21.9	19.7
11:15 A.M.	Young shoot, growing region, direct sun	17.1		
			23.6	25.2
			24.4	25.8
Mar. 25, 11:30 A.M.	Young shoot, near base, shaded growing region	23.4	27.2	26.1
			27.6	26.4
10:30 A.M.	Young shoot, growing region, direct sun	19.6	24.5	25.1
Mar. 26, 11:30 A.M.	Young shoot, growing region, direct sun	20.3	23.3	23.7

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Factors Affected by Temperature Changes.—In all parts of the plant the temperature effects on diffusion rate, imbibition (31), and osmotic pressure (42) will come into play; with a high probability of further differences due to changes in phase equilibrium in the protoplasm (16). Compounds with large molecules, as sugars and amino acids, will have much higher temperature coefficients of diffusion than simple electrolytes.

In storage tissue we have new problems, especially the temperature coefficients of enzyme action (15). The reserve food in the asparagus seed is largely fat, so that we have to deal with a lipase. Starch is absent, but there are probably some inulin-like polysaccharides. In the storage roots the reserve is mainly sugar (40), which probably undergoes enzymatic change into a more readily translocated form. Morse (40) shows that the nitrogen in the roots is not appreciably drawn upon for the formation of the amino acids and proteins of the shoots. Therefore, these must be built up from reserve sugar and the nitrates absorbed by the roots as the process goes on. It is probable that the synthesis of the amino acids occurs in the roots, so that it is the soil temperature that will affect the rate of this process.

As is indicated in the discussion of light effects, photosynthesis is of minor importance in the growth rate of young asparagus shoots. Therefore, it will be passed over with only a reference to work by Spoehr (58, 60) and Osterhout (48).

In the growing region the problem of temperature effects becomes so complex that any temperature coefficients (4, 24, 47) obtained are merely the approximate composite effects upon many different reactions. The components of the protoplasm, proteins, lipoids, and complex pentosans and hexosans are being constructed from the amino acids, simple sugars, and mineral salts that are supplied. Each of the reactions represented in these processes may well have its own temperature coefficient, and as each goes on there is a continual change in imbibitional and osmotic relationships.

Simultaneously with these syntheses, and supplying the energy for them and for the mechanical forces of growth, sugars of simultaneous synthesis and decomposition upon temperature coefficients is discussed by Osterhout (47). According to the figures of Morse (40), half the sugars used from the roots must be oxidized; more, if any considerable amount of photosynthesis occurs in the young stalks.

The Effect on Sprouting and Germination.—No attempt was made to discover the lowest temperature at which a crown would send out shoots. Shoots were produced at 15°C., if the soil was kept fairly wet, but roots could be kept at 17°C. without sprouting if the ground were only barely moist. The lowest soil temperature recorded was 8.7°C., at 9:30 a. m.

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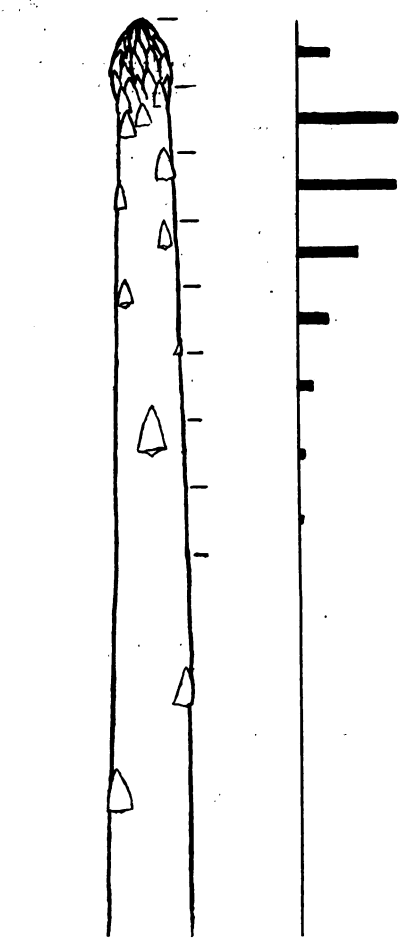

Fig. 4—The length of each of the heavy horizontal lines indicates the amount of growth of an asparagus shoot in 24 hours, of the 1 cm. section opposite.

February 7, 1921, at which time it was rising rapidly. This would indicate a minimum at least as low as 6°C., with an air temperature several degrees lower. Continuous growth was recorded during this time; thus growth continued, for the comparatively short period of the exposure, at a temperature much too low for its inception.

Seeds were planted in soil at a depth of 7 mm. At 15°C. (soil temperature) it took 32 days for the seedlings to appear; at 20°C., 22 days and at 24°C., 15 days. In the glass house, with average daily temperature variation between 16° and 30°C., it took 18 days for the appearance of the seedlings. In two experiments where seeds were germinated between cloths, the temperatures during the one ranging from 15° to 20°C., and during the other from 21° to 25°C., only one or two days' difference was noted in the average time of the first breaking of the seed coats. Apparently the much longer time necessary for seedlings to appear at the surface of soil at the temperatures of 15° to 29°C. is due more to slow growth than to slow germination.

The Effect on Growth Rate.—For comparison with temperature changes, with figures given by other workers, and between seedlings and shoots from storage roots, growth rates have been computed in six ways (9, 12). These may be indicated as follows: If L = mean length of the growing region for the period measured, ΔLda = total elongation in one day, ΔLhr = total elongation in one hour, S = mean length of the most rapidly growing region marked (usually 5 mm.$+\frac{1}{2}\Delta$S), and ΔS

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its growth increment, with subscript indicating the period: $\Delta Lda/1440$, $\Delta Lhr/60$, $\Delta Lda/1440 \cdot L$, $\Delta Lhr/60 \cdot L$, $\Delta Sda/1440 \cdot S$, and $\Delta Shr/60 \cdot S$ (approximated from the ratio, $\Delta Sda \cdot \Delta Lhr/60 \cdot S \cdot \Delta Lda$). The last two methods give comparatively smaller values with seedlings than with shoots, because the 5 mm. sections marked represent a much larger proportion of the total growing region. Table IV gives the computed growth rates for a number of individuals at various times.

However, in this study, the growth curve as traced by the auxograph is probably the most useful means of comparing the growth of shoots of approximately the same age. This is because factors which increase or decrease the growth rate change the length of the growing region in the same direction (with a certain lag). This fact may be observed in the figures of Büchner (9), though it is not mentioned. With a very few exceptions, the plants of any species which he measured fall in the same order whether arranged according to mean daily growth rate, or mean length of the growing region. One might not be seriously in error in saying that the length of the growing region is a function of the preceding growth rate. It must be taken into consideration, of course, that the increasing length of the growing region magnifies an apparent increase in growth rate, and vice-versa.

Figure 2 shows the daily growth and distribution of the growing region of a young shoot at a fairly even temperature, about 21°C. The shoot was marked daily into 5 mm. divisions, and each line in the figure shows the height above the soil of one of the points marked. This shoot is listed as No. 53 in Table IV.

In the same manner, Fig. 3 shows the growing region of a young seedling, which is listed as No. 76 in Table IV. The length of each of the heavy horizontal lines in Fig. 4 indicates the amount that the 10 mm. section opposite it on the stalk grew in the following 24 hours. This shoot is No. 29 in Table IV.

Figure 5 is a copy of the auxographic record of stalk No. 40, grown in the glass house. Figure 6 gives the computed maximum and minimum growth rates, and the maximum and minimum soil and air temperatures. A copy of the thermograph record is given for several days, and the growth rates plotted at frequent intervals for part of the time. Fig. 7 shows the auxographic record, the computed growth rates, and the soil temperature of shoot No. 42, grown in the dark chamber. The daily variations of the air temperature, as well as of the soil temperature, were too small to be read on a thermometer divided by 0.2°. The reason for the abruptness of the changes in slope of the auxographic tracing is not known. The curved lines of the original auxograph sheet somewhat mask the abrupt changes, but careful observation reveals them, and a careful recheck proved the plotting correct.

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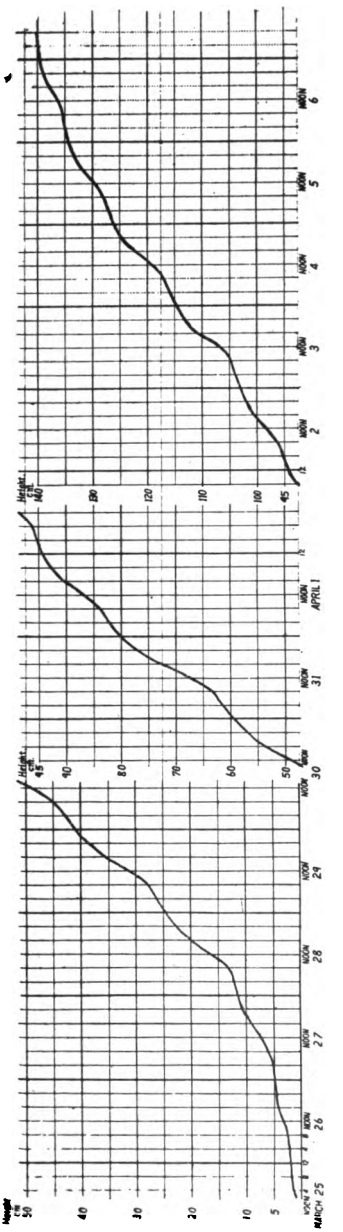

Fig. 5—Growth curve of asparagus stalk number 40, in glass house.

Figure 8 is a copy of the auxographic record of stalk No. 41, grown in the light, at temperatures not varying more than 2° from 19°C.

Shoot No. 5, growing in a rich black loam soil, was watered with 0.01 M. NaCl solution at 11:30 a. m. February 21. Figure 9 shows its growth curve, growth rate, and the soil temperature curve. The action of the NaCl seems to be responsible for the abrupt increase in growth rate.

Figure 10 gives the auxographic record, maximum and minimum growth rates, and maximum and minimum soil temperatures for an asparagus seedling, No. 73.

The accurate measurement of increase in diameter of a very young asparagus stalk is difficult, because rapid elongation is going on at the same time, and the stalk is not stiff enough to support any instrument yet devised; moreover, at first the stalk is entirely covered with leaves. A micrometer caliper was especially fitted with fine tips on the jaws to get between the leaves as early as possible. A point as near the tip as could be measured was marked with India ink, and the diameter there measured daily, with the results shown in Table V.

A lever set and "permant" steel frame, as used in the MacDougal dendograph (35), were arranged to bear upon a young stalk at a point 6 cm. above the

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TABLE IV.—MAXIMUM, MINIMUM, AND MEAN GROWTH RATES OF ASPARAGUS STALKS (IN MILLIMETERS PER MINUTE).

No.	Date	Soil temp.	Air temp.	ΔLda 1440	ΔLhr 60	ΔLda 1440-L	ΔLhr 60-L	ΔSda 1440-S	ΔShr 60-S
40	Mar. 1922	2	2	0.020	0.031				
	26	20	18.5	0.024	0.012	0.00049		0.00085	
		26	29		0.045		0.00090		0.00158
	27	19	17	0.063	0.014	0.00079	0.00028	0.00147	
		30	34.5		0.071		0.00089		0.00165
	28	20.5	20	0.103	0.029	0.00069	0.00036	0.00124	
		28	30		0.133		0.00089		0.00160
	29	18.5	17	0.123	0.061	0.00056	0.00041	0.00117	
		27.5	28.5		0.170		0.00078		0.00163
	30	23	21	0.129	0.075	0.00056	0.00034	0.00112	
		31	34		0.191		0.00083		0.00165
	31	25	23	0.135	0.078	0.00056	0.00034	0.00105	
		33	37		0.218		0.00091		0.00170
	Apr. 1	21.5	20	0.083	0.070	0.00035	0.00029	0.00076	
		24	25		0.143		0.00057		0.00125
	2	17	15.5	0.059	0.043	0.00030	0.00018	0.00079	
		19	20		0.090		0.00045		0.00120
	3	15	14	0.087	0.039	0.00046	0.00019	0.00082	
		28.5	31.5		0.167		0.00088		0.00158
	4	19	18	0.073	0.046	0.00049	0.00024	0.00086	
		29	32.5		0.125		0.00084		0.00148
	5	21	19.5	0.047	0.035	0.00039	0.00024	0.00078	
		26	28		0.084		0.00070		0.00140
	6	19.5	18	0.034	0.017	0.00028	0.00014	0.00068	
		25	26		0.059		0.00049		0.00118

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TABLE IV—(CONTINUED)

No.	Date	Soil temp.	Air temp.	ΔLda 1440	ΔLhr 60	ΔLda 1440·L	ΔLhr 60·L	ΔSda 1440·S	ΔShr 60·S
5	Feb. 18	15		0.005		0.00020			
41	Apr. 2			0.009		0.00030			
	3			0.013		0.00033			
	4			0.028		0.00040			
	5			0.040		0.00042			
	6	mean		0.045		0.00041			
	7	19		0.051		0.00041			
	8			0.059		0.00039			
	9			0.067		0.00041			
	10			0.071		0.00041			
	11			0.078		0.00040			
42	Apr. 19			0.008		0.00027			
	20			0.012		0.00027			
	21			0.015		0.00030			
	22			0.015		0.00027			
	23	mean		0.019		0.00031			
	24	15.5		0.027		0.00032			
	25			0.033		0.00033			
	26			0.035		0.00032			
	27			0.031		0.00028			
	28			0.031		0.00026			
29	Feb. 29	20.5		0.036		0.00034		0.00060	
53	Apr. 12			0.021		0.00042		0.00057	
	13-14	21		0.003		0.00046		0.00062	
	14-15			0.047		0.00046		0.00057	
	15-16			0.054		0.00047		0.00057	
76	Nov. 16			0.0024		0.00040		0.00046	
	17-18			0.0035		0.00041		0.00055	
	18-19	19.5		0.0059		0.00046		0.00067	
	19-20			0.0090		0.00048		0.00049	
	20-21			0.0111		0.00056		0.00057	
	21-22			0.0167		0.00084		0.00073	
	22-23			0.0139		0.00070		0.00066	
73	Apr. 14	30.5			0.0058		0.0012		
	15	21		0.0036	0.0003	0.0005	0.0001		
		28			0.0094		0.0009		
	16	22.5		0.0069	0.0025	0.0007	0.0003		
		33			0.0163		0.0016		

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TABLE IV—(CONTINUED)

No.	Date	Soil temp.	Air temp.	ΔLda 1440	ΔLhr 60	ΔLda 1440·L	ΔLhr 60·L	ΔSda 1440·S	ΔShr 60·S
73		21			0.0011		0.0001		
	17			0.0069		0.0005			
		30			0.0164		0.0011		
		20.5			0.0020		0.0001		
	18			0.0088		0.0006			
		31.5			0.0210		0.0014		
		22			0.0031		0.0002		
	19			0.0080		0.0004			
		32			0.0189		0.0010		
		21.5			0.0017		0.0001		
	20			0.0045		0.0005			
		32.5			0.0097		0.0010		
		21			0.0008		0.0001		
	21			0.0026		0.0005			
		33			0.0050		0.0010		
		23			0.0010		0.0002		
	22			0.0024		0.0005			
		33.5			0.0048		0.0010		
		22			0.0009		0.0002		
	23			0.0015		0.0003			
		31			0.0028		0.0006		
71	Jul. 11	24		0.0028					
	12-13	27		0.0042					
	13-14	23		0.0021					
12	Apr. 2	26		0.087					
	3-4	14		0.040					
	4-5	12		0.021					
	5-6	20		0.036					
	6-7	22		0.054					

surface of the soil. The record copied in Fig. 11 was obtained, beginning as soon as elongation had ceased at the point of bearing. A slight growth was recorded, covering a period of 4 or 5 days. Checking of growth is shown at from 8 to 10 a. m. on each day. The later record shows clearly the daily fluctuations in diameter, shrinkage starting as the transpiration increases in the morning, and rapid initial recovery between 6 and 8 p. m., followed by gradual increase until 4 or 6 a. m.

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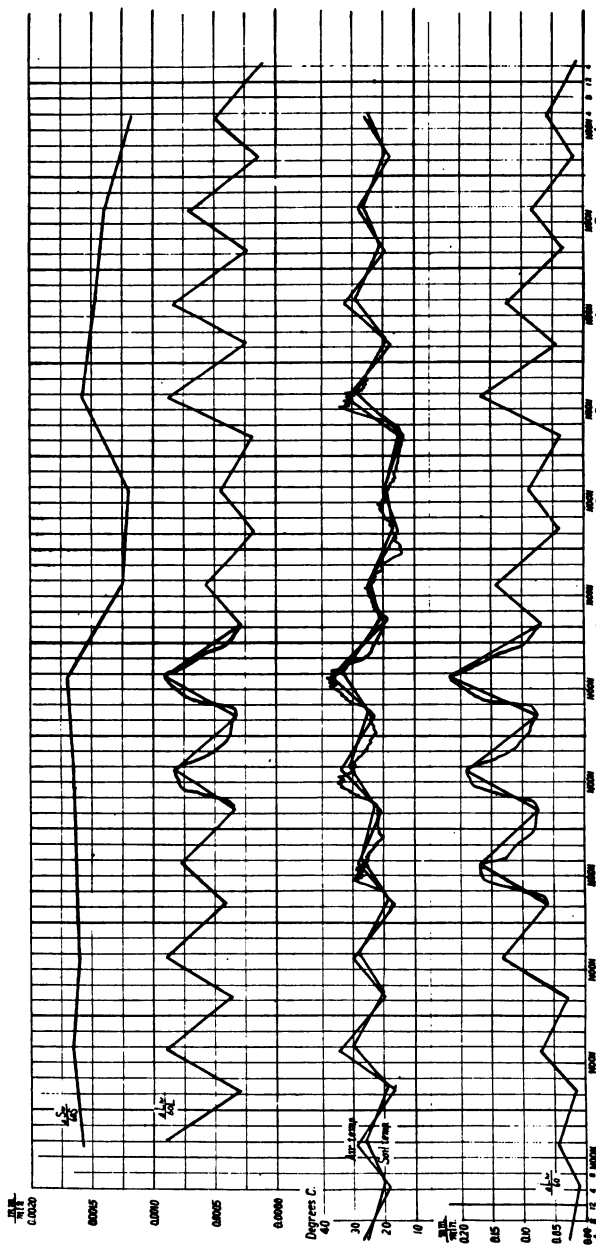

Fig. 6—Maximum and minimum growth rates and maximum and minimum soil and air temperatures for asparagus stalk number 40.

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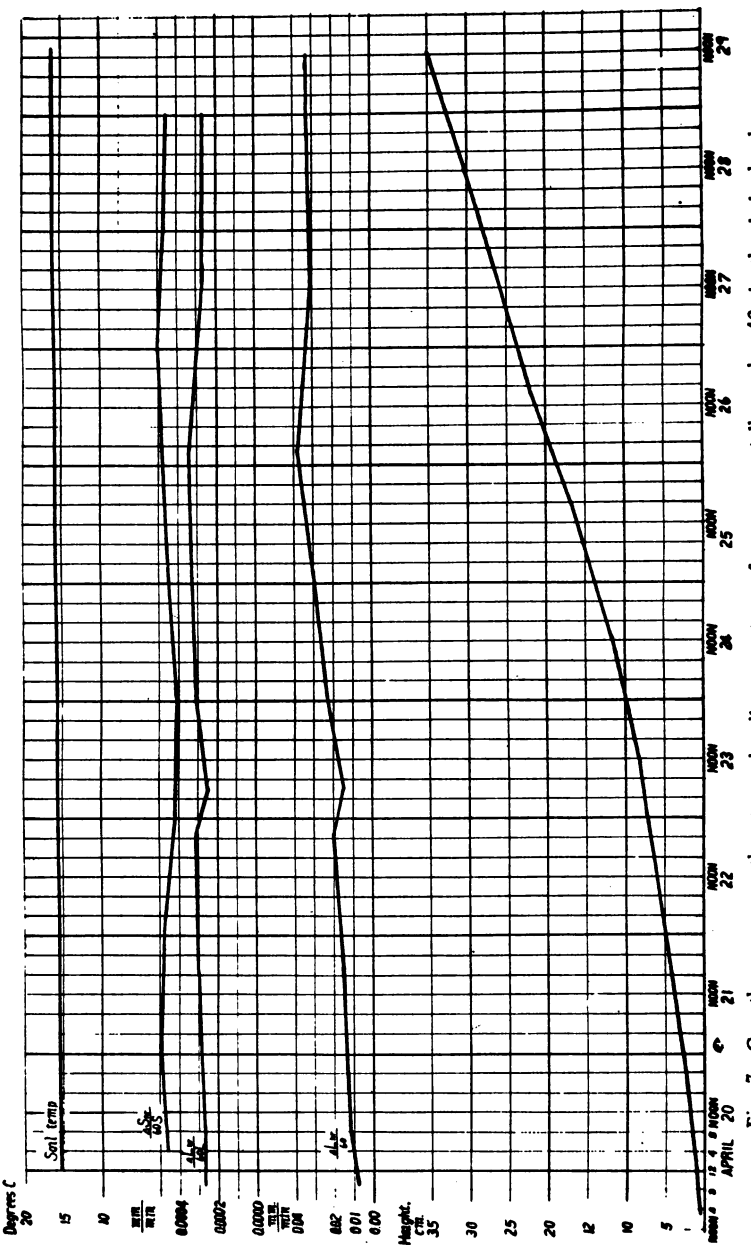

Fig. 7—Growth curve, growth rate, and soil temperature of asparagus stalk number 42, in the dark chamber.

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TABLE V.—DAILY GROWTH IN LENGTH AND DIAMETER OF ASPARAGUS STALKS.

Date April	Diameter at point marked	Distance of point from tip	Distance of point from soil
	mm.	mm.	mm.
12	4.61	16	19
13	4.66	21	42
14	4.73	39	76
15	4.92	90	98
16	5.10	192	98
17	5.12	337	98

Temperature the Chief Factor in Branching.—Among growers it is often suggested that the early branching of young shoots, which concludes the cutting season, may be due to the depletion of the reserve food material in the roots. To determine whether this was the case, four strong crowns were set in a pot in the glass house on January 28. No shoots were allowed to grow to a height of more than 20 cm. In April the day temperatures were reaching as high as 35° to 40°C., and the shoots from this pot were beginning to branch when only 6 or 8 cm. in length. On April 17 the pot was moved to the constant temperature room, at 15°C. The shoots produced there grew slowly, but attained the height of 75 to 100 cm. before showing any branching at all. Further, comparable plants were set in the sunlight, one in the glass house where the temperature ran as high as 40°C., and the other in the laboratory where the temperature did not go above 24°C. The shoots of the former began branching when they were 6 to 8 cm. high, while those from the latter did not branch until they were 20 to 25 cm. in height. From this, and from the experiment mentioned previously as to the effect of light, it seems that the time of branching is chiefly a function of the temperature.

The Effect on Hydration Capacity.—As growth and hydration are intimately related, it was desired to learn the effect of temperature on the hydration of asparagus. Trios of sections from the same shoot were swelled simultaneously in water under the auxograph at temperatures of 16° and 23°C. Swellings of 4.4 percent and 4.8 percent, respectively, were recorded. Even a greater difference was observed in the time necessary to attain the maximum swelling, as is shown by the copies of the swelling curves in Fig. 12.

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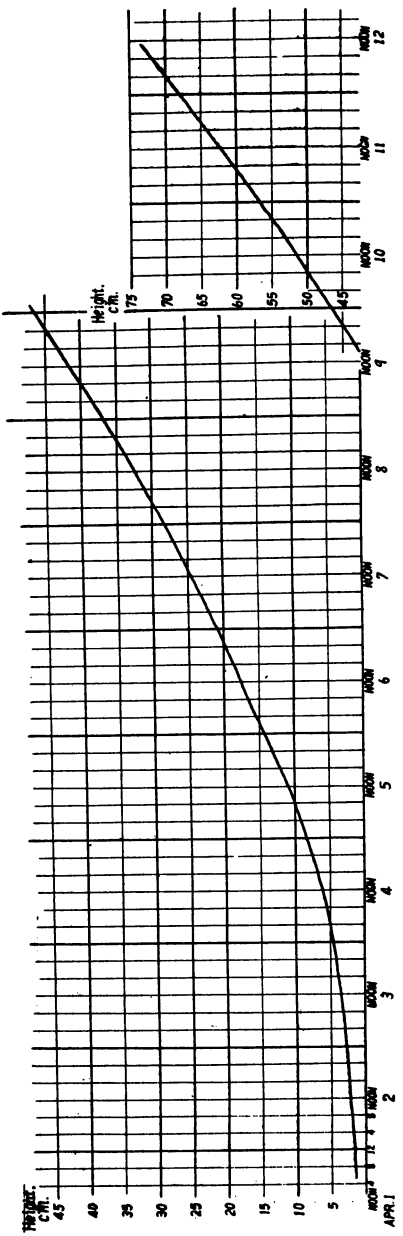

Fig. 8—Growth curve of asparagus stalk number 41, in light at equable temperature.

THE EFFECT ON GROWTH OF THE CHEMICAL ENVIRONMENT OF THE SOIL

Solution Cultures. — The common belief in the benefit of applying common salt to asparagus suggests that there may be some specific action for either the sodium or the chlorin. Experiments showing that KCl is preferable to other potassium salts as a fertilizer (41, 64) indicate the possibility of a chlorin effect, but it may be worth noting that $NaNO_3$ was also being applied. Swelling experiments indicate that sodium salts in 0.001 normal concentration increase hydration, while among the anions Cl takes a place between NO_3 and SO_4. To get further information on this matter, two series of sand cultures were started. Wide mouth quart fruit jars were seasoned with hot dilute sulphuric-dichromate solution according to the method of Duggar (14), and then with dilute HCl. A good grade of fine quartz sand was obtained from the Philadelphia Quartz Company of Berkeley. For the coarser substrata, pure crystalline quartz was gathered from the washes at the foot of the Santa Catalina Mountains and crushed at the ore dressing laboratory of the University of Arizona, through the courtesy of Dean G. M. Butler.

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The sand and crushed quartz were treated first with the sulphuric-dichromate solution and then with dilute HCl. Washing with distilled water was continued until after the wash waters showed the same PH (colorimetrically) as the original distilled water. Coarse, and then finer, crushed quartz was used to nearly half fill the jars, and the sand then put in on top. Glass tubes were run nearly to the bottoms of the jars so that the sand could be drained and aërated by suction.

Twenty-five seeds were planted in each jar, but only ten plants were allowed to grow. Distilled water was used for the germination and until 2 days after the seedlings had begun to appear at the surface. Several extra cultures were started in each series and the poorest discarded. The jars were arranged to get practically equal illumination, and their positions were interchanged daily. During the experiment the night temperatures varied from 12° to 22°C. and day temperatures from 22° to 30°C.

Shive's R_5C_2 solution (55) was the basic solution used for series A and the R_6C_1 solution of Livingston and Tottingham for series B; with the exception that the source of iron in both cases was 0.01 g. of "soluble ferric phosphate" per liter in each solution (14). The salts used were "Baker's Analyzed" or Merck's blue label, except the $Ca(H_2PO_4)_2$ and the soluble ferric phosphate, which were Merck's white label and U. S. P., respectively. The KH_2PO_4 was recrystallized, and the PH of a solution of it was between 4.5 and 4.6. The PH values of the complete solutions ranged from 5.2 to 5.4 in series A, and from 5.2 to 5.6 in series B. No explanation is offered to account for the difference between these values and those Duggar (41) found. The PH of a solution of the $Ca(H_2PO_4)_2$ alone was 4.6. On April 3, the solutions drawn from the culture jars tested PH 5.3 to 5.4 in both series. The growth of the plants had decreased the differences in PH between the different solutions, but left them more acid than Hoagland's barley cultures (21).

The solutions were all applied very liberally and the excess drained out, to avoid any very great concentration by evaporation.

The seed was planted for series A on January 20, 1922, but on account of the low temperatures in the unheated glass house, the seedlings did not appear until February 18. Germination was poor, so that some of the jars had less than ten plants, and the general appearance was not so good as that of the plants of series B. For these reasons the results of series B are considered somewhat more reliable. The molar concentrations of the solutions of series A are given in Table VI. Numbers 2 and 3 were parallel, as were numbers 4 and 5, and 6 and 7, with the exception that one solution was adjusted to the same osmotic concentration as No. 1, and the other to the same NO_3 concentration. The plants of No. 7 were all dead March 8, and those of No. 6, March 10. The rest of the plants were pulled April 10, cut just above the remains of the seed, and dried

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and weighed; then burned and the ash weighed. The results are given in Table VII. The effect of the entire absence of calcium is plainly shown

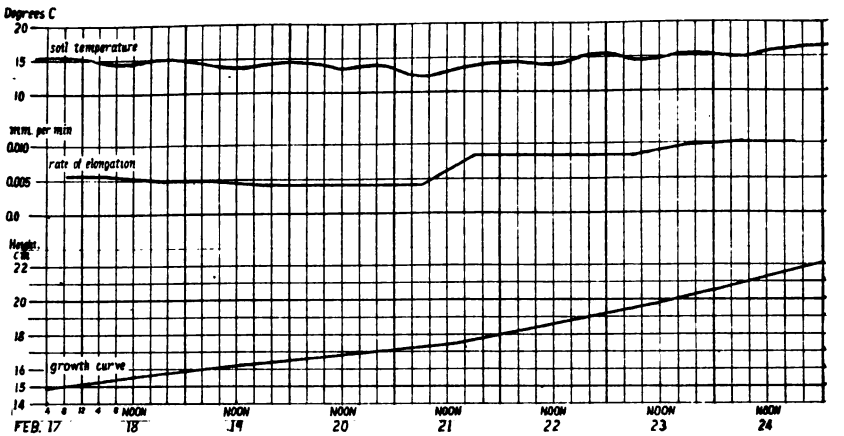

Fig. 9—Growth curve, growth rate, and soil temperature curve of asparagus stalk number 5, watered with 0.01 molar NaCl, beginning February 21.

by 6 and 7. There is apparently an improvement by the reduction of the Mg in 8, and perhaps in 10, 12, and 13. The effects of sodium, calcium, and magnesium seem to agree fairly well with those in series B, and will be discussed in connection with them.

The seeds were planted for series B on February 3, and the seedlings appeared February 23. Germination was good, and a large number of extra cultures allowed the choice of very similar groups of plants for the different solutions. The molar concentrations of the solutions are given in Table VIII. Solution 9 has Na, Ca, and Mg present in about the concentrations found in ocean water, while 8 omits the excess Mg, and 7 the Ca and Mg. These three were not applied full strength until March 10. On March 25, all of 9 had died, and all of 7 on March 28, but some of 8 lasted until April 7. The plants from the remaining cultures were gathered April 14. Dry weight and ash are given in Table IX.

The injurious effect of magnesium, (26, 51, 28) even though present with sodium and calcium in the proportions found in ocean water, is clearly shown in Nos. 6 and 9. It is perhaps the magnesium which causes the shortening of the life of the asparagus beds in the lower islands of the Sacramento River, where brackish water is carried up by the tide.

In solutions 7, 8, and 9 the osmotic pressure of the NaCl alone would be between 20 and 25 atmospheres (42), and there was also a slight increase in concentration of all the solutions by evaporation. Growth con-

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TABLE VI—COMPOSITION OF CULTURE SOLUTIONS IN SERIES A.

Solution	KH_2PO_4	$Ca(NO_3)_2$	$MgSO_4$	$NaNO_3$	Na_2SO_4	NaCl	$CaCl_2$	$MgCl_2$
1 A	0.0180	0.0052	0.0150					
2 ANa_1	0.0180	0.0039	0.0150	0.0018				
3 ANa^1	0.0180	0.0039	0.0150	0.0026				
4 ANa_2	0.0180	0.0013	0.0150	0.0053				
5 ANa^2	0.0180	0.0013	0.0150	0.0078				
6 ANa_3	0.0180		0.0150	0.0071				
7 ANa^3	0.0180		0.0150	0.0104				
8 ANa_4	0.0180	0.0026	0.0075	0.0052	0.0075			
9 ACl_1	0.0180	0.0052	0.0150			0.0200		
10 ACl_2	0.0180	0.0026	0.0075	0.0052	0.0075	0.1000		
11 AMg_2	0.0180	0.0026	0.0075	0.0052	0.0075	0.1000		0.0038
12 ACl_3	0.0180	0.0026	0.0075	0.0052	0.0075	0.2000		
13 ACa_2	0.0180	0.0026	0.0075	0.0052	0.0075	0.2000	0.0042	
14 AMg_3	0.0180	0.0026	0.0075	0.0052	0.0075	0.2000	0.0042	0.0226

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tinued so long with solution 8 under the existing adverse conditions of temperature and evaporation that the following experiment was carried out. Soil was thoroughly dried and put in a sealed pot. It was then wet with solution 8 and asparagus roots planted in it. The first watering was

TABLE VII—WEIGHT OF SEEDLINGS OF SERIES A, MARCH 10.

Culture	No. of plants	Dry weight	Dry weight per plant	Ash	Ash per plant	Ash per g. dry wt.
1 A	10	0.2583	0.02583	0.0566	0.00566	0.219
2 ANa_1	9	0.2714	0.03016	0.0573	0.00637	0.211
3 ANa^1	9	0.2994	0.03327	0.0689	0.00766	0.230
4 ANa_3	10	0.2418	0.02418	0.0549	0.00549	0.227
5 ANa^3	10	0.3941	0.03941	0.0843	0.00843	0.214
6 ANa_5	6	0.0525	0.00875	0.0091	0.00152	0.173
7 ANa^5	7	0.0646	0.00923	0.0134	0.00191	0.208
8 ANa_4	8	0.3038	0.03798	0.0671	0.00839	0.221
9 ACl_1	9	0.1995	0.02217	0.0475	0.00528	0.238
10 ACl_2	10	0.2962	0.02962	0.0850	0.00850	0.287
11 AMg_2	10	0.2423	0.02423	0.0762	0.00762	0.314
12 ACl_3	8	0.2255	0.02820	0.0663	0.00829	0.294
13 ACa_3	7	0.2301	0.03287	0.0762	0.0189	0.331
14 AMg_3	3	0.0608	0.02027	0.0195	0.00650	0.321

also with solution 8; thereafter, distilled water was used. The young shoots from this pot showed no noticeable difference from other shoots, but in the old stalks the number of needle-like branches, the so-called "leaves", was greatly reduced. No other noticeable effect was produced during 7 weeks.

The yield was improved in all pots where sodium was added except at the concentration of 0.5 molar, and with solution 6, where it is thought that the large amount of magnesium caused the lesser growth. The fact that in solutions 2 and 3 the sodium replaced part of the potassium is, of course, no indication that it took the place of the potassium in the metabolism of the plants. These solutions have a large excess of the elements over the requirements for growth. The increase in growth with sodium occurred in spite of the fact that the already very high per-

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TABLE VIII—COMPOSITION OF CULTURE SOLUTIONS IN SERIES B.

Solution	KNO_3	$Ca(H_2PO_4)_2$	$MgSO_4$	$NaNO_3$	NACl	$CaCl_2$	$MgCl_2$
1 B	0.0216	0.0026	0.0150				
2 BNa_1	0.0108	0.0026	0.0150	0.0108			
3 BNa_2	0.0054	0.0026	0.0150	0.0162			
4 BCl_1	0.0216	0.0026	0.0150		0.0500		
5 BCl_2	0.0216	0.0026	0.0150		0.2000		
6 BMg_2	0.0216	0.0026	0.0150		0.2000	0.0016	0.0076
7 BCl_3	0.0216	0.0026	0.0150		0.5000		
8 BCa_3	0.0216	0.0026	0.0150		0.5000	0.0080	
9 BMg_3	0.0216	0.0026	0.0150		0.5000	0.0080	0.0415

centage of ash was also increased; in fact, the increase in dry weight of 5 over 4 is largely a gain in ash. The chlorin ion did not show the

TABLE IX—WEIGHT OF SEEDLINGS OF SERIES B, APRIL 14.

Culture	No. of plants	Dry weight	Ash	Ash per g. dry weight
		g.	g.	g.
1 B	10	0.2239	0.0465	0.208
2 BNa_1	10	0.2960	0.0613	0.207
3 BNa_2	10	0.3511	0.0883	0.252
4 BCl_1	10	0.2786	0.0886	0.317
5 BCl_2	10	0.3058	0.1085	0.355
6 BMg_2	10	0.2033	0.0748	0.368
7 BCl_3	10	0.1247	0.0392	0.315
8 BCa_3	10	0.1486	0.0561	0.378
9 BMg_3	10	0.1190	0.0378	0.318

specific action that might have been expected from fertilizer work reported by Morse (41) and Thompson (64). Though the calcium in No. 8 seemed to protect at least partially against the toxic effect of the high concentration of sodium, it gave the highest percentage of ash in any of the cultures. This agrees with the results of Le Clerc and Breazeale (25), and of Reed (52), which indicate that the addition of the calcium

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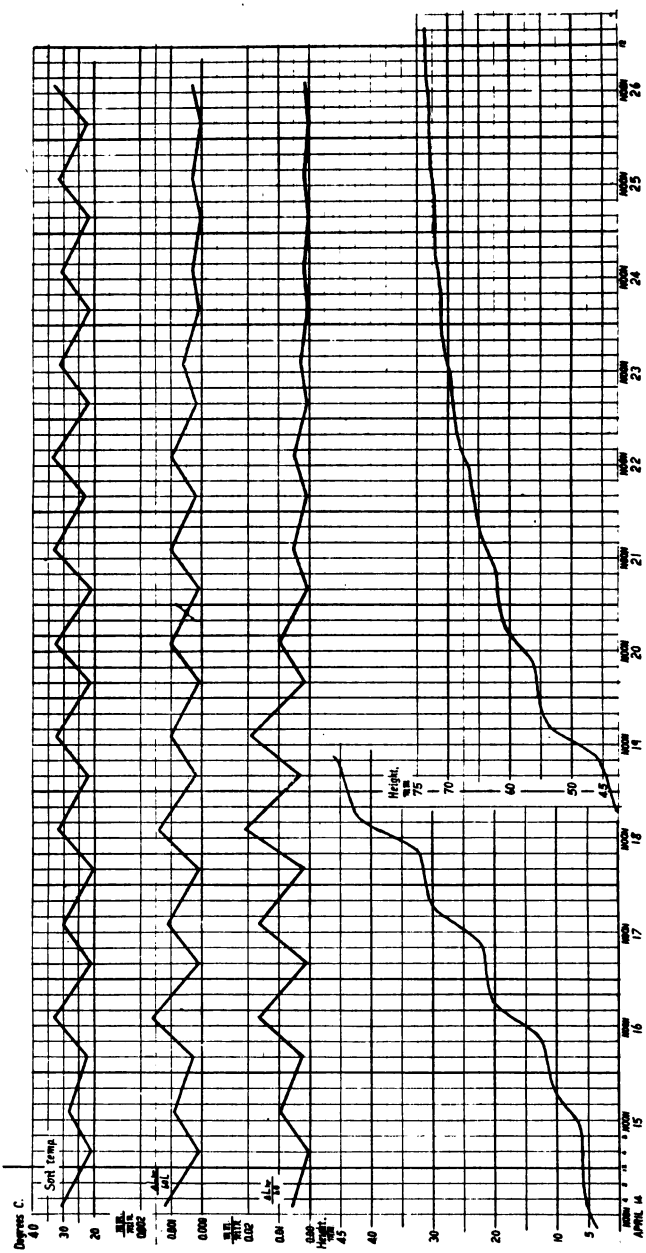

Fig. 10—Growth curve, maximum and minimum growth rates, and maximum and minimum soil temperatures for asparagus seedling number 73.

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does not decrease the amount of sodium which may finally enter. Stiles (61) has emphasized the importance of the absorption equilibrium and the rate of absorption, and Brooks (7) has shown a lessening of the rate of absorption in the presence of antagonistic salts. Osterhout's later theory of antagonism (46) gets entirely away from the idea of one salt preventing the entrance of another. In his discussion of "The Significance of Calcium for Higher Green Plants", True (67) brings out admirably the effect of the lack of calcium, and the necessity of a certain "equilibrium concentration". However, the action of the calcium should probably be very greatly broadened. First, it is probable that the "pectin" and "pectic acid" of Fremy, Mangin, Chodnew, and others are by no means identical compounds in the different plants in which they are found, but are merely very complex mixed pentosans, with similar solubilities, which may be broken down into similar or identical substances. In other words, the term pectin probably should be used much as is the term albumin among the proteins; possibly True intended this meaning. At any rate, almost any of the complex acids obtained by the oxidation of the plant pentosans give insoluble calcium salts. But, especially, it should be emphasized that calcium salts, except in exceedingly dilute solution, reduce the hydration and permeability of agar and of gelatin alone, and of the various agar-protein biocolloids, as shown by MacDougal (31, 33) and MacDougal and Spoehr (36, 37). Any of the higher fatty acids present (33) will collect at the phase boundaries and will form insoluble calcium soaps in the presence of that element. The action of the lipoids in the cell is just beginning to be understood, but a few simple experiments have shown that they have great possibilities in affecting the reaction of the cells to Ca and Mg. A bit of lecithin spread in a thin layer and covered with water gradually hydrates, and, at least with a very slight shaking, finally forms a water emulsion. As the lecithin in the plant cell is surely finely divided, and is surrounded by a large proportion of water, it doubtless takes this form. Lecithin was rubbed up into such an emulsion and various reactions tried. Ordinary, and even fairly high, concentrations (0.01 M up to 1.0 M) of Na and K salts have no visible effect upon the emulsion—thus meeting the objections of Osterhout (44) and others that a lipoid layer would not permit the entrance of salts. But Ca and Mg salts in fairly high concentrations (0.1 to 1.0 M) will be seen to flocculate the lecithin in a few hours. Still further, 1.0 M NaCl will prevent or delay this flocculation by 0.1 M $CaCl_2$. However, the fact that the lipoids give these reactions should not lead to the assumption that all changes in the permeability of the cell are due to their flocculation or solution (5, 17, 22). This would be as inadequate as the assumption of the same function for pectic acid and calcium pectate. As it is well stated by MacDougal (34),

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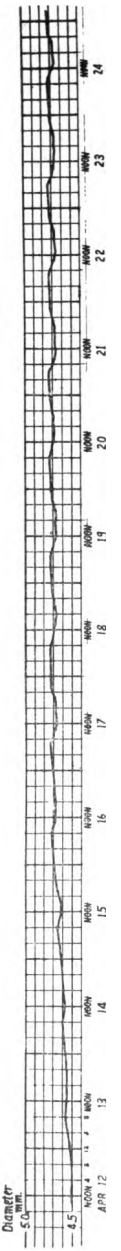

Fig. 11—Increase and daily variations in diameter of asparagus stalk.

"All substances which may appear in the cell in the colloidal condition of reversible gels must be taken into account in any adequate interpretation of cell-action, particularly growth."

In drawing conclusions from the results of these cultures, the following facts should be kept in mind:

1. The basic solutions were adjusted for the growth of wheat in water cultures, and therefore are not necessarily properly balanced for asparagus seedlings in sand cultures.

2. Under different conditions of temperature, humidity, illumination, and the like, differently proportioned solutions are required for optimum growth.

3. Seedlings may show somewhat different reactions than established plants, and sand cultures than field cultures.

4. The plants in these cultures did not appear as healthy as seedlings grown in soil, the tips being somewhat chlorotic. Increasing the amount of iron in one of the extra cultures did not improve this; and the high total concentration (6, 21) is not considered to be at fault because the condition was no worse in the cultures receiving additional salts as NaCl. That it may be the result of magnesium injury is suggested by the fact that Livingston and Tottingham found that these solutions give magnesium injury with wheat (26).

Chemical Effect on Germination and Sprouting.—The slow germination of asparagus seed (18) has already been mentioned. The ordinary methods of hastening delayed germination, such as treatment with H_2SO_4 and scarification, had no appreciable effect. In this case the slowness is evidently that characteristic of fatty seeds, and is due to the slow action of the lipolytic enzyme. Soaking in fairly hot water hastened the swelling of the seed and seemed to cause germination earlier by the amount of time gained in soaking. This suggested the trial of other methods of increasing the rate of the initial hydration. Treatment with solutions of saponin gave the results listed in Table. X. The effect is seen to be slight but unmistakable. For comparison, the saponin treatment was

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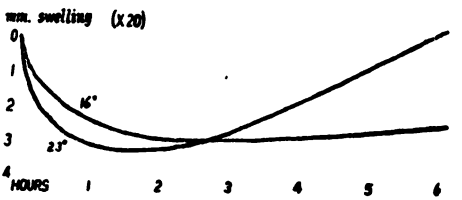

Fig. 12—The effect of temperature upon the amount and rate of hydration in asparagus.

tried on other types of seeds, with results as shown in Table IX. With the alfalfa seed an increased rate of hydration is shown, and a slight hastening of germination. The seeds of *Erythrina flabelliformis* and *Parkinsonia microphylla*, on the other hand, are impermeable on account of a waxy coating (65) which is not dissolved by the saponin solution, and therefore no effect is produced.

Asparagus roots were also treated with dilute saponin solution in the hope of obtaining quicker sprouting. The results given in Table XII indicate that metabolic activity was hastened in some manner by the treatment. There is some reason to suppose that it is due to a slight increase in permeability, such as is produced by dilute solutions of sodium salts. If this is the case, the saponin treatment was beneficial for the same reason that a certain concentration of sodium salts is beneficial.

THE HYDRATION CAPACITIES OF ASPARAGUS TISSUES

Tests of the hydration capacities of sections of asparagus stalks and roots were made according to the method of MacDougal (31), a tangential slice being removed to permit unhampered swelling. Now the growing region of even very young asparagus stalks will have a length of several centimeters, so that sections for the swelling tests can all be taken from the younger portion of this region. Still, experiment showed that sections from the apical and middle portions of the growing region did not have the same swelling capacity. This is easily understood from the fact that near the tip the cells are in an elementary form, increasing in size chiefly by imbibition, with vacuoles small if present at all (34). Further down the stalk, the cells have increasingly larger vacuoles, and osmosis plays a greater and greater part. Because of this difference, special care in sampling is necessary if comparable results are to be obtained. Figure 13 indicates a method of selection by which three trios of sections with almost identical hydration capacities may be obtained. If more sets are desired in one series, a similar method is used on two or three stalks, having in each trio the same number of sections from any particular stalk.

The percent swelling of one series of sections in water (or any of the solutions used) is not directly comparable with that of another series, because of differences in water deficit, due to varying humidity, soil

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TABLE X—THE EFFECT OF SAPONIN TREATMENT ON THE GERMINATION OF ASPARAGUS.

Expt.	Weight 50 seeds	Treatment	Percent increase in wt.	Percent germination after				Temp. range
				5 da.	6 da.	8 da.	14 da.	
1	1.0215	H_2O, (5 hours)	8.0		0	18	44	
2	1.0248	0.025% saponin	8.2		2	26	52	15°
3	1.0023	0.075% saponin	8.1		2	34	52	to
4	0.9853	0.150% saponin	8.7		4	26	44	20°
5	0.9828	0.375% saponin	8.8		0	20	44	
6	0.9537	H_2O, (17 hours)	24.10	4	16		48	
7	0.9426	0.025% saponin	25.30	6	20		54	20°
8	1.0244	0.075% saponin	23.36	8	24		52	to
9	0.9875	0.150% saponin	25.04	6	18		54	25°
10	1.0075	0.375% saponin	25.12	8	22		50	

moisture, and the like. But if the stalks have been grown under nearly enough similar conditions that their composition and colloidal condition are the same ratio, % swelling in 0.001 M. NaCl% swelling in water, should be a constant. That this is the case is attested by the fact that a large number of determinations of this ratio give the typical probability curve of Fig. 14. The figures given in Table XIII are the mean values of several to many determinations of the ratio of the percent swelling in the solution named to the percent swelling in water. The swelling of the young shoots, etiolated young shoots, and seedlings agree fairly closely. The increased swelling in NaOH may be in part due to combination with asparagin and other amino acids present, but, if one may judge from the lessened swelling in acids, it is probably largely attributable to pentosans, mucilages, and the like (31, 33, 36, 37). The reduced swelling in the amino acids is clearly the result of the considerable percentage of those compounds already present (40), as the roots show an increased swelling in them. Sodium salts (27) at 0.001 normal cause greater hydration than the balanced solution (0.001 NaCl + 0.000,02 $CaCl_2$), both in fresh and dried shoots. This slight increase in hydration is probably the cause of the improved growth in the presence of sodium salts.

Two other methods were used in the determination of swelling capacity. In one, the growing region of young stalks was divided longitu-

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dinally into four sections. One of these was placed in water, the others in the solutions to be tested. Percentage swelling was computed from measurements with a millimeter scale. The percentage swelling averaged a little greater than that measured transversely by the auxograph, but the swelling ratio, computed as above, agreed very closely.

Sections 2 or 3 millimeters long were cut from the very young

TABLE XI—THE EFFECT OF SAPONIN TREATMENT ON THE GERMINATION OF ALFALFA, CORAL BEAN, AND PALO VERDE.

No.	Material	Weight 50 seeds	Treatment		Percent gain in wt.	Percent germination after 2 da.	3 da.	5 da.
1	Alfalfa	0.0863	H_2O	3 hours	81.0	32	96	96
2		0.0900	0.025% saponin	3 hours	82.3	46	96	98
3		0.0737	0.075% saponin	3 hours	94.6	52	96	98
4		0.0838	0.375% saponin	3 hours	88.7	40	94	96
1	Erythrina flabelli-	4 seeds 2.9552	H_2O	18 hours	0.01	no germination		
2	formis	2.8108	0.075% saponin	18 hours	0.02			
3		2.7983	H_2O	6 days	0.03			
4		2.9618	0.375% saponin	6 days	0.02			
1	Parkinsonia microphylla	6 seeds 0.8719	H_2O	18 hours	0.00	no germination		
2		0.8410	0.075% saponin	18 hours	0.01			
3		0.8572	H_2O	6 days	0.01			
4		0.8835	0.375% saponin	6 days	0.00			

portion of the stalk, and their swelling in both the longitudinal and transverse axes was measured by means of a microscope with a micrometer eyepiece. Swelling was uniformly a little greater in the longitudinal

TABLE XII—THE EFFECT OF SAPONIN TREATMENT OF ASPARAGUS ROOTS.

Weight, 3 crowns	Treatment	Percent gain	Planted	Date of appearance of shoots: first	second	third	fourth	fifth
265.1 g.	H_2O (20 min.)	7.6	March 31	Apr. 5	Apr. 12	Apr. 21		
253.8	0.075% saponin	8.5	March 31	Apr. 7	Apr. 10	Apr. 12	Apr. 17	Apr. 21

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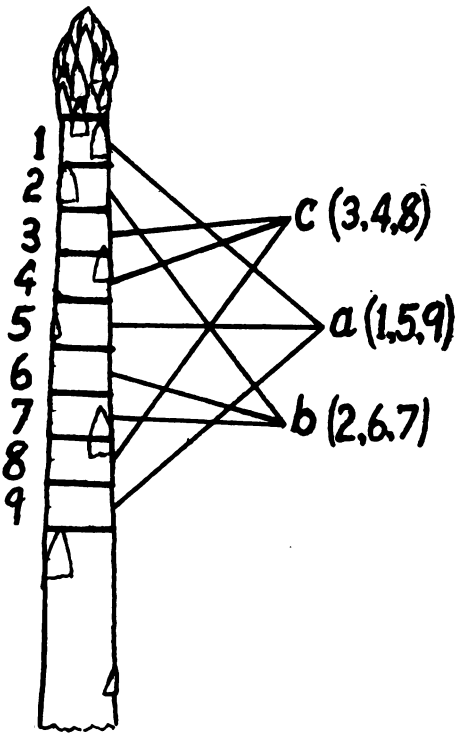

Fig. 13—Method of selecing trios of sections of asparagus stalks which have equal hydration capacities.

axis, and the swelling ratios agreed well with those measured by the auxograph.

CONCLUSIONS

1. Shoots comparable in composition may be obtained at different times of the year if similar roots are taken from cold storage and forced for equal lengths of time.

2. Light has little or no immediate effect on the growth rate of young shoots or seedlings, or on the height they attain before branching. Its effect is chiefly through the food stored from previous photosynthesis.

3. Light is an important factor in the production of new roots. (It is suggested that this may be a result of the change in carbohydrate gradient due to photosynthesis.)

4. The three external factors of greatest importance in the growth rate of the young shoot are the temperature, the moisture content of the soil, and the salt balance of the soil.

5. Increase of growth rate was always found with increasing temperatures up to the highest which occurred during the experiments.

6. Temperature cannot be considered a limiting factor in the narrowest sense of the word, as an improvement in the salt balance of the soil induces more rapid growth at the same temperatures.

7. The height attained by the stalk before branching is governed chiefly by the temperature. If exhaustion of reserve food has an appreciable effect, it is observed first in the production of stalks of smaller diameter, preventing satisfactory comparison.

8. The addition of sodium salts in medium or low concentration improved the salt balance of the soils and nutrient solutions used.

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TABLE XIII—VALUE OF THE RATIO $\frac{\text{PERCENT SWELLING IN SOLUTION}}{\text{PERCENT SWELLING IN WATER}}$ FOR SECTIONS OF ASPARAGUS SHOOTS IN VARIOUS SOLUTIONS.

	0.01 HCl	0.001 HCl	0.01 NaOH	0.001 NaOH	0.01 NaCl	0.001 NaCl	0.01 Balanced	0.001 Balanced	0.001 $NaNO_3$	0.00002 $CaCl_2$	0.001 Normal Na_2SO_4
Young shoots	0.78	1.07	0.97	1.04	0.98	1.11	0.98	1.02	1.31	1.01	1.05
Etiolated shoots	0.75	0.98	1.01	1.12	1.00	1.13	0.97	1.01	1.37	0.99	1.07
Dried shoots	0.51	1.14	1.03	1.29		1.07		1.03		1.06	
Young seedlings	0.80	1.05	0.98	1.07	0.97	1.12		1.03	1.28	1.02	
Old stalks	0.83	0.93	0.96	1.01		1.02		1.00		0.98	
Roots	0.77	1.03	0.93	1.02	0.94	1.08		0.98		0.87	

	0.01 asparagine	0.01 glycocoll	0.001 glycocoll	0.001 histidine 0.001 glycocoll	0.001 KCl 0.001 histidine 0.001 glycocoll
Young shoots	0.77	0.88	0.95	0.74	0.81
Old stalks	0.94	0.89	0.95	0.97	0.89
Roots	1.08	1.19	1.05	0.91	1.08

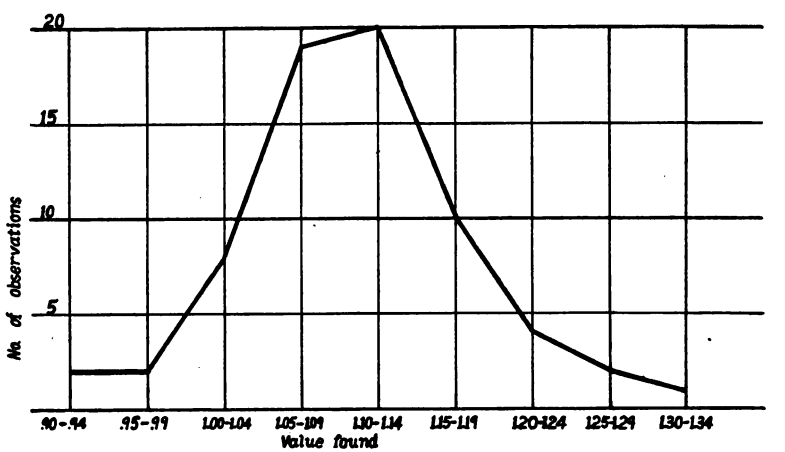

Fig. 14—Probability curve of the values found for the ratio, $\frac{\text{percent swelling in 0.001 molar NaCl;}}{\text{percent swelling in } H_2O.}$

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9. The amino acids present in the young stalk are favorable to high imbibitional swelling of a protoplasm containing a large percentage of pentosan.

10. Temperatures favorable for commercial growth will be limited on the one side by the reduced growth rate and on the other by the early branching induced. The color, texture, and slope of the soil will be important as regulating soil temperature, of especial importance when white asparagus is grown.

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AGR. REFERENCE BOOK

Technical Bulletin No. 6 January 15, 1926

University of Arizona
College of Agriculture
Agricultural Experiment Station

GIFT
JUL 26 1926

THE REACTION BETWEEN CALCIUM SULPHATE AND SODIUM CARBONATE, AND ITS RELATION TO THE RECLAMATION OF BLACK ALKALI LANDS

By J. F. Breazeale and P. S. Burgess

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FOREWORD

This technical bulletin is the first of a series that will appear from the Agricultural Chemistry Section dealing with problems relating to alkali soils, and to plant growth under irrigation.

In the arid Southwest, practically all agricultural lands must first be reclaimed from the desert, and the reclamation of desert lands is by no means an easy problem. Even if successfully reclaimed and brought under cultivation, the natural tendency of all our arid lands is to revert to their natural desert condition, and nothing but the most intelligent efforts of man can prevent this.

In the history of mankind this fight against the slow forces of nature in arid countries has been a losing one, and, except in the Valley of the Nile, where irrigation has been carried on under peculiar conditions, we have yet to find a single example of a permanent irrigation agriculture.

Foremost among these destructive agencies that bring about this reversion is alkali, and it is believed that the problems relating to alkali are the most important problems now facing the irrigation farmers of Arizona.

In handling problems that are as complex as are those of reclamation, a knowledge of the fundamental factors involved is most essential. We must have a thorough understanding of many phases of soil alkali and methods of controlling it if we can hope to maintain a permanent agriculture.

The present paper deals with one of the most important chemical reactions that take place in the reclamation of alkali lands—that involved when gypsum is added to black alkali soil. A study of this reaction has brought about some new conceptions of several conditions that are associated with black alkali; for example, it explains why it is impossible to neutralize completely black alkali or sodium carbonate by the addition of gypsum or calcium sulphate; it explains why the addition of organic matter with an application of gypsum is so essential, and why carbon dioxide cannot be present in a black-alkali soil.

J. J. THORNBER,
Director.

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LIFE HISTORY AND HABITS OF THE THURBERIA BOLLWORM, *Thurberiphaga diffusa* BARNES (*Noctuid*)

By C. T. Vorhies

INTRODUCTION AND HISTORICAL SKETCH

Late in the year 1912 a variety of cotton boll weevil* was found breeding in the plant known as wild cotton (*Thurberia thespesioides* A. Gray) in the mountains of southern Arizona. Announcement of this discovery early in 1913 by Cook (5) aroused interest in other insects for which this plant might be the host, because of the possibilities of infestations with new pests which might result from growing cultivated cotton in valleys contiguous to the wild plants. *Thurberia*, while a small-fruited plant, (Fig. 1) bearing on its seeds only short and scanty fiber, is nevertheless more closely related to *Gossypium* than any other genus of malvaceous plant. While at first sight it may not appear to any but a botanist to have close resemblances to cotton, a little familiarity with both plants soon discloses many striking similarities. The general infestation of *Thurberia* with a weevil closely resembling the all-too-well-known Mexican boll weevil, leads naturally to the inference that the insect pests of the one plant might readily become pests of the other. This conception was greatly strengthened in 1915 when Coad (3) showed that the Thurberia weevils would readily attack domestic cotton if favorable opportunity offered. It is further strengthened by the fact that another insect, a small moth† probably native to the wild cotton, (12) has become so widely distributed and well known as a cotton insect in Arizona and southern California that its real origin is almost lost sight of. This insect is well known as the "cotton leaf perforator" (11) and is common throughout the cotton-growing regions above mentioned. Fortunately, because of its small size and the nature of its work, it ordinarily does no appreciable damage. In the season of 1924, however, it was reported to have been distinctly injurious in the Imperial Valley and Yuma districts.

**Anthonomous grandis thurberiae* Pierce.

†*Bucculatrix thurberiella* Busck.

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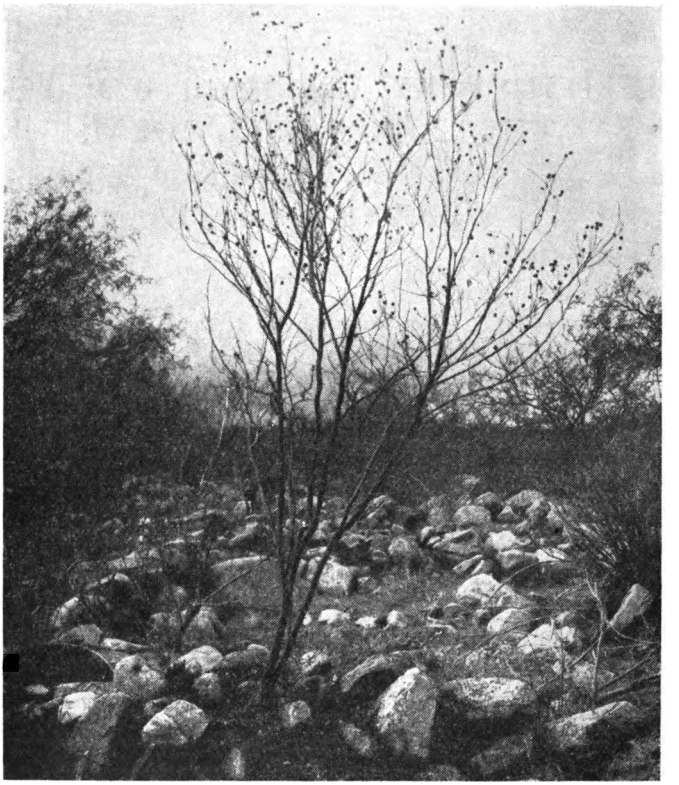

Fig. 1.—A specimen of *Thurberia* in winter condition, showing the numerous small bolls. This crop of bolls is rather less than average.

Pierce and Morrill in 1914 (12) made a study of the insects taken on *Thurberia*, as a result of which they listed 83 species thus found. These they classed as "injurious 25, nectar visiting 40, parasitic 12, and predacious 6, in their purposes of visiting the plant." In their publication is noted for the first time the bollworm which is the subject of the present investigation, the moth not having been connected up with the larval stages until some years later. The authors begin their account of the worm with the following significant statement (p. 17): "The Thurberia boll worm is considered the most destructive of all the insects attacking Arizona wild cotton." Also (pp. 18-19), "The Thurberia boll worms appear to feed upon Egyptian cotton as readily as upon the wild cotton." Morrill, in personal conversations with the author of this bulletin has also urged the advisability of investigating the possibilities of transfer of this insect to cultivated cotton.

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In view of these evident possibilities, it was decided in 1920 to undertake an investigation of the details of the life history and habits of this insect, as well as to seek facts bearing upon its possible adaptability to cotton under cultivation.*

In the autumn of 1918, Dr. C. H. T. Townsend of the United States Department of Agriculture, spent several weeks in camp in Sabino Canyon in the Santa Catalina Mountains making observations on the Thurberia bollworm. A manuscript report of his work (14) was made available to the present author by the late Dr. W. D. Hunter of the Federal Horticulture Board. This report was valuable in the present investigation as a point of departure, affording dates of activity and other data from which to work. Townsend succeeded in carrying a number of these bollworms through to pupation. These pupae, 22 in number, were then sent to Washington, and later transferred to Louisiana and Texas points for overwintering. From these there issued at Brownsville and Victoria, Texas, August 2 to September 1, 1919, a total of nine specimens, three of which were damaged by careless handling.† Five of these, three males and two females, were cotypes for the description of "A New Noctuid from Arizona" by H. G. Dyar (6). Dyar described this not only as a new species but as a new genus under the name *Thurberiphaga catalina, (Lepidoptera, Noctuidae)*.

It has since been determined that this species was first described by Barnes as *Alaria diffusa*, (2) only the moths being known to him. Dyar's new genus is now recognized as valid, but *catalina* sinks as a synonym, and the correct scientific name becomes *Thurberiphaga diffusa* Barnes (7). Mr. Foster H. Benjamin has kindly compared our specimens with the types of *diffusa* in the Barnes collection.

DESCRIPTIONS

THE MOTH

Barnes' description (2) of the imago (Fig. 2a) follows:

"*Alaria diffusa*, n. sp. —♀ expanse: 35 mm. Head and palpi pink, antennae yellowish-brown, collar flushed with pink at base, yellow above. Thorax pale yellow, abdomen a little darker, more dusky-yellow than thorax. Primaries clear pale yellow, showing, however,

*Moreland, after our investigations were begun, reported (10) "The Thurberia boll worm seems to be far more destructive than the Thurberia weevil. The worm infestation in 1921 was much heavier than that of the weevil and judging from the worm sign in the 1920 crop of bolls the worm damage was also greater than the weevil the previous year. In some places fully one-fourth of the 1920 crop of bolls had been eaten out by the worms."

†Webb, (15) reporting Townsend's findings, records the emergence of a tenth individual at Brownsville on August 28, 1920.

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under the lens a slight dusting with orange scales between the veins, barely discernible to the naked eye in some places as faint longitudinal streaks. The pink markings are arranged as follows: From middle of, but not quite reaching costa there is a well-marked blotch, quite well defined, which runs downward and outward across cell, here it makes a well-marked angle and is continued to middle of inner margin as a somewhat narrower band, parallel to outer margin. This median band is connected with a marginal band by a broad shade in the middle of the wing, which is sharply defined above, but gradually fades into the yellow below. The marginal band leaves the external margin just below apex, and is narrow and sharply defined above the connecting shade, below it is not so sharply limited, and fades out as it reaches the inner angle.

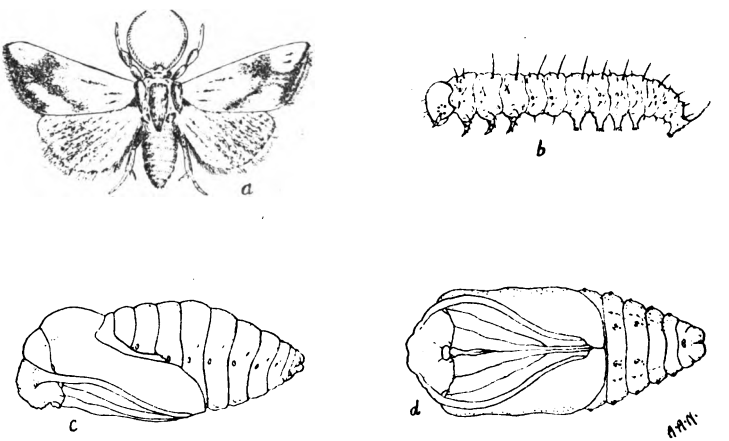

Fig. 2.—(a). Adult *Thurberiphaga diffusa*, about life size;
(b). Newly hatched larva, x 21;
(c). Pupa, x 3½;
(d). Pupa, x 3½.

These bands divide the wing into three areas, a basal to the median shade, one above outer half of inner margin, and one below outer half of costa. The first two are not so sharply defined on the borders which are formed by the pink bands, as these are here more diffuse and shade into the yellow, the last, however, is clear cut at its outer and lower sides. The outer edge of the marginal band is regularly toothed, the points just reaching the basal fringe line. The filling between the teeth is yellowish, dusted with pink. The fringe is pink outwardly, somewhat lighter yellowish internally, basal line pink, not very distinct. Secondaries pale yellowish, quite thickly dusted with pink over outer half of wing, forming a broad

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pinkish band from costa, fading out shortly beyond middle of wing. Fringe concolorous.

"Beneath primaries quite thickly dusted with pink, except along inner margin and a subapical patch, which are yellow. Secondaries have a pink blotch at middle of costa, from which a faint, broad and diffuse mesial band runs partly across wing, disappearing about the middle.

"Type: 2 ♀'s, Arizona, Huachuca Mts., August; Santa Catalina Mts., August 24-30. The latter specimen from Mr. Poling."

This is a very beautiful moth for a Noctuid. Its colors are practically identical with the colors of the withering flowers of *Thurberia* (pink and white), so much as to suggest at once a protective resemblance, but, unfortunately for this conception, we have never found the moth resting in or on any stage of the flower. The freshly opened blossom is pure white.

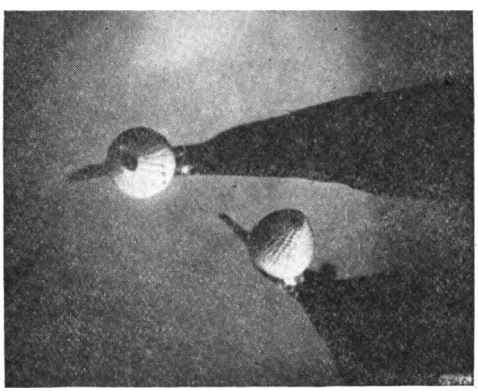

Fig. 3.—Eggs of *Thurberiphaga diffusa* on tips of Thurberia leaves, x 11.

Detailed studies of the life history of *Thurberiphaga diffusa* were begun in 1920, but, owing to lack of knowledge of the insect and its habits, little was learned of the early stages in that season. These studies were continued in 1921, 1922, 1923, and 1924, as a result of which the details are now well understood.

THE EGG

The dates and characteristic manner of oviposition will be described in connection with the fruiting habit of the plant. The egg (Fig. 3) of this moth was well described by Pierce and Morrill (12) as follows:

"The egg is pure white in color, truncate-conical in form, with crater-like apical depression. Greatest diameter 0.79 to 0.83 mm.; height, 0.79 to 0.8 mm.; diameter of entrance to apical cavity,

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0.13 mm.; edges ragged. Surface of eggs marked with slightly depressed reticulations forming polygonal cells, small at base of the eggs and gradually increasing in size as the diameter of the egg decreases. About 52 cells occur around largest circumference and about 21 cells around smallest circumference. As the embryo develops the egg gradually becomes distinctly pinkish."

The present author would add to this only the observation that the fresh eggs usually show a greenish tinge through the white shell and later become distinctly pink as described.

THE LARVA

The newly hatched larva is from 1.3 to 1.5 mm. in length, stretching to 2 mm. when crawling (Fig. 2b). It is straw to orange-yellow in color, with brown head, and is relatively more hairy than the last instars. The second instar larva is fairly dark red in color, while the third and fourth instars are especially so. Pink is not at all a proper designation for the color in these stages. The usual color is near oxblood red (13). Heads are light to darker brown, depending upon whether early or late in the instar. The larva in the last instar reaches a length of 23-24 mm., stretching to 25-26 mm., with a width of 5 mm. It is relatively smooth, with light brown head and prothoracic shield, and also a light brown anal shield. The body is light green in ground color, with more or less of a reddish blush over the green. Distinct red blotches bound the black spiracles, giving the effect of an interrupted lateral band of pink or reddish. The dorsal vessel, carrying greenish blood, is distinctly visible.

THE PUPA

"The pupa is robust, measuring about 10 mm. in length, and 5 mm. in width. It is light brown in color with dark brown spiracles." Pierce and Morrill (12). (Fig. 2c, d).

The above description can hardly be improved upon for brevity. The pupa lies in a cell formed in the soil by construction of a rather dense and resistant cocoon, about 15 mm. in length. The writer, as well as Moreland (10), has conducted diligent search under Thurberia plants to a depth of 3 to 4 inches in attempts to find the pupal cocoons in nature, but without success. In pots or jars in the laboratory the cells are formed at a depth of 1.5 to 2 inches, but the depth may well be greater in the open, and the larvae may wander to considerable distances from the plants before entering the soil.

NATURAL ENEMIES

While a few Braconid parasites were reared from bollworms collected in the field in the earlier years of the investigation, the later phases of

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the work dealt increasingly with larvae hatched indoors or under screen, far removed from the normal habitat of *Thurberia*, and hence free from parasites. As the work proceeded it seemed more and more evident that the bollworm was not potentially dangerous to cotton. For these reasons no organized effort was made to study the parasites, and no further details from our own work will be offered. Townsend recorded a parasitism of 29 percent of the larvae, four species of hymenopterous parasites having been reared by him. His results have been published by Webb (15), and are readily available to those interested.

No egg parasites have been discovered. Occasionally eggs were found which appeared to have been robbed of their contents by some sucking insect. While we have sometimes found hollowed-out Thurberia bolls torn open, presumably by birds, we have not observed so large a percentage thus attacked as was mentioned by Townsend, who reported in one case about 5 percent, and in another 10 percent of infested bolls destroyed by birds, probably Arizona Jays.

DISTRIBUTION OF PLANT AND BOLLWORM

All data concerning the distribution of the host plant *(Thurberia thespesioides)* of this insect as known up to 1922 have been brought together and summarized by Hanson (8). His publication includes a distribution map compiled from these data. To the information thus published we can add for the purpose of this report two important items. On the eastern bahada of the Sierrita Mountains, *Thurberia* occurs abundantly in a number of washes which empty into the Santa Cruz River about opposite Continental. The plant has also been found in the Tortillita Mountains since the publication of Hanson's bulletin. It will not be necessary to discuss further in this publication the distribution of the host plant, but a map showing the known distribution of the bollworm is presented (Fig. 4). In addition to the author's personal observations on the occurrence of bollworm infestations on *Thurberia*, all available records of collections of the moths have been compiled and mapped. As will be seen later from the account of the habits of the insect the capture of moths in a given locality is fairly conclusive evidence of occurrence of larvae in *Thurberia* not very far distant.

CORRELATION IN ACTIVITY OF PLANT AND BOLLWORM

FRUITING PERIOD OF *THURBERIA*

As there exists a close correlation between the seasonal activity of the insect and its host plant, some discussion of the normal growth and fruiting habit of the latter is necessary. *Thurberia* is a deciduous, perennial shrub, occasionally attaining almost the stature of a tree. Its habitat

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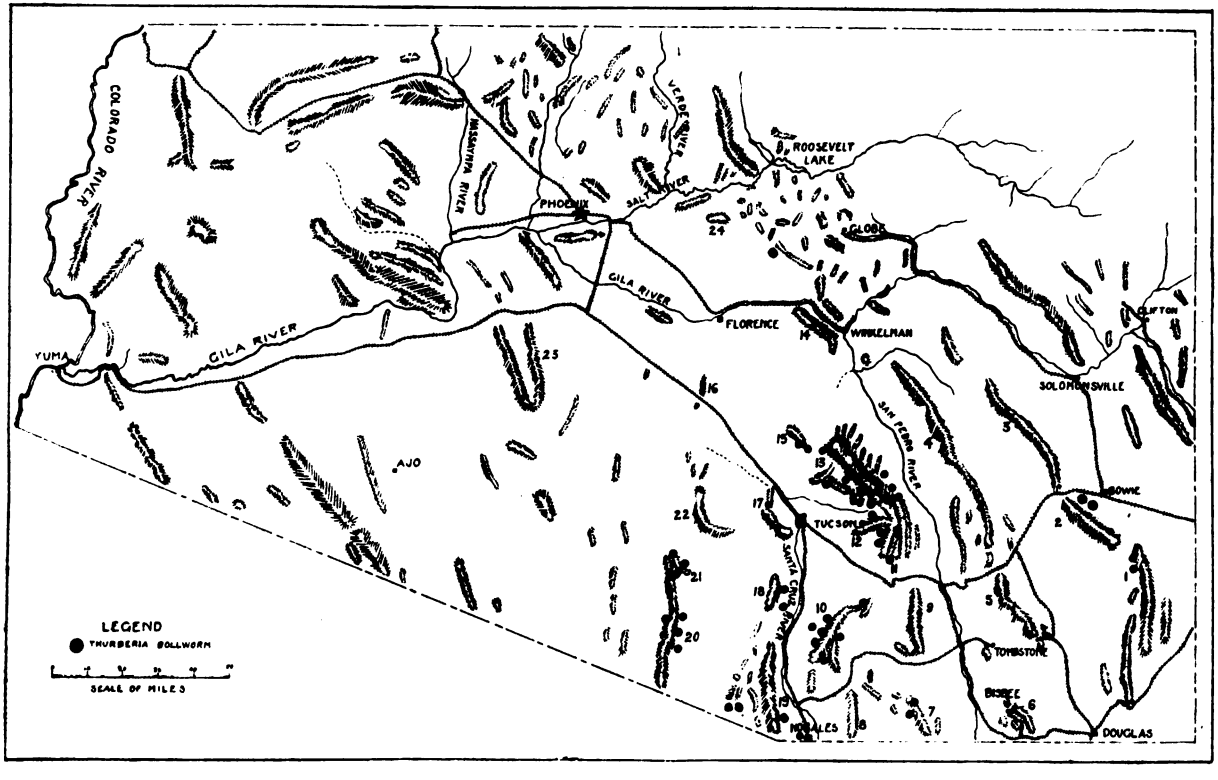

Fig. 4.—Map of the southern part of Arizona showing the present known distribution of the Thurberia bollworm in the mountain ranges. Thurberia plants occur in many places which have not been checked for bollworm infestations.

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Key to the names of mountains indicated by number on the map:

1. Chiricahua Mts.
2. Dos Cabezas Mts.
3. Pinalino Mts.
4. Galiuro Mts.
5. Dragoon Mts.
6. Mule Mts.
7. Huachuca Mts.
8. Patagonia Mts.
9. Whetstone Mts.
10. Santa Rita Mts.
11. Rincon Mts.
12. Tanque Verde Mts.
13. Santa Catalina Mts.
14. Tortilla Mts.
15. Tortillita Mts.
16. Picacho Mts.
17. Tucson Mts.
18. Sierrita Mts.
19. Tumacacori Mts.
20. Baboquivari Mts.
21. Coyote Mts.
22. Roskruge Mts.
23. Maricopa Mts.
24. Superstition Mts.

in the mountain canyons is in the main well described by Coad (3), (4), Hanson (8), and Bailey (1), though the present author would emphasize the fact that at the higher elevations it is much less confined to the stream-beds, and much more promiscuously scattered over the mountain sides, while at lower levels, 2,200-4,000 feet, and outside the canyons proper, it is practically confined to the sand washes. This wider distribution in the higher and rougher parts of its range is most important to recognize in any discussion of the possibility of eliminating its insect pests, as, for example, through eradication of the plant. Another point of importance is the fact that its normal flowering and fruiting period is in the autumn. The present author during several successive years of observation has been generally unable to find plants in bloom or fruiting before late August, or evidence, in the form of new fruits of the year, that blooms were formed in the spring. At a little higher altitude in the canyons not even leaves appear on the plants until May. The normal blooming period begins in the latter half of August, first blooms appearing in a notable number of instances on or very near to August 25. This brings the fruiting period into September. It may be added that once the autumn blossoming and fruiting has begun, a great profusion of buds, flowers, and fruits develops rapidly, when moisture conditions are at all good. Fruiting continues into October. We believe that the above represents what may legitimately be called a normal blooming and fruiting period of *Thurberia*, though there occur occasionally some notable exceptions. Coad (3) (4) as a result of his observations made in the season of 1914 described in considerable detail what he conceived to be the seasonal activity of *Thurberia*, beginning with heavy squaring by May 1, and blooming about May 7 at the lower altitudes, then a progressively later beginning as higher and higher altitudes were reached, plants above 5,000 feet not starting to square until August. The plants noted at the low altitudes, moreover, produced in 1914 a series of crops amounting in a few cases to four, and in many cases to three. Coad says, however, (4): "Regardless of the

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previous activity of the plants, the last crop of fruit (produced during August and September) is always the largest and blooming extends over a longer period of time. Most of the plants stopped blooming during the latter part of September, though quite a few continued blooming into early October." The quoted statement agrees with our observations of several years. Unfortunately for the general conclusions which it was natural for Coad to draw from his observations, 1914 could hardly have been a normal season. During 5 or 6 years prior to the 1924 season, only once has exception to the autumn fruiting period been noted. This exception was in line with Coad's observations in 1914, but only a single small spring crop of bolls was noted. The year 1924 was exceptionally dry in southern Arizona in the summer months, and a bewildering variety of exceptions to the usual fruiting activity was observed. Many plants perished from the drought. Other groups more favorably situated bloomed with a greater or less degree of normality, but at different times. A group of plants in one location might be found blooming freely by mid-August, while another not many miles away, or even not many rods away, might not bloom until the normal late-August period. Moreover, as we went from place to place on this and Thurberia weevil work we noted many individual plants and sometimes small groups of plants which had borne some fruit in the early season. Fruits of the year, though ripe and dehiscent, may be readily distinguished by their gray-green color from the old, brown, weathered bolls of the previous year. Also in a few instances, green bolls in mid-August indicated a late-July or early-August blooming. At the same time (late August) notably in Sabino Canyon, individually fortunate plants were in full bloom, though with drooping foliage, while the majority had very few or no blossoms, and many others were quite dead. Coad further says (4): "The active period of the plant will probably vary with the different years according to climatic conditions. The winter of 1913-14 was exceptionally mild and consequently some of the lower plants may have started blooming earlier this season than is usual."

While agreeing in general with the above statements the present author is inclined, on the basis of the observations of several years previously mentioned, to believe that the active blooming period varies less than Coad had cause to assume, and that there is at least an equal chance that a deficiency in moisture during the winter of 1913-14 was a co-factor, if not the chief one, causing the abnormal blooming of 1914. Examination of the records of the United States Weather Bureau shows a supranormal mean temperature for each of the first 5 months of 1914, amounting to a total of $+11.4°$ departure from normal. Precipitation records

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for the same 5 months show deficiencies for January and February amounting to 1.04 inches, a smaller surplus in March of .45 inch, a deficiency for April of .31 inch which, however, was a 100 percent deficiency, there being no rain in that month. In May there was .49 inch of rainfall, a .38 inch departure from normal but it is unlikely that this affected the blooming since it occurred in the first week of May. Whether a 33 percent deficiency in rainfall or a monthly surplus of approximately three degrees in mean temperature is of the greater importance we are not prepared to say. Aside, however, from the fact already mentioned that in 1924, an extremely dry year, we found the greatest number of exceptions to the rule, we found that with an abundance of water, *Thurberia* growing in the introduction gardens on the University Campus showed no exception. Here, at an elevation even less than the lowest at which plants were studied by Coad, the luxuriantly growing plants have only once been observed by the writer to put forth a single blossom prior to late August, generally the first being noted very near to August 25. There is no lack of either heat or moisture here, since the altitude is but 2,400 feet and the gardens are frequently irrigated. We have here simply an example of the fact that an abundance of moisture is favorable to vegetative growth, without tendency to force fruiting, while low moisture which is yet above the minimum at which the plant can live does force fruiting (9). Plants which were apparently about to die from extreme drought in 1924 had but very few or no blossoms even in the normal fruiting period.

ACTIVITY OF THE MOTH

As will now be shown, the normal habit of the moth is closely correlated with what we have termed the normal fruiting period of the plant. The moths fly to strong light such as that from a gasoline mantle lamp or lantern, a Coleman lantern of 300-candle-power having been used in this investigation. The author has never taken a moth prior to August 15. In the Barnes collection, however, are specimens taken between August 1 and 7 in the Santa Catalina Mountains, by Poling.* From August 15 to about September 15 they may be readily taken on favorable nights. In our experience, however, they have appeared neither earlier than 9 p. m. nor later than midnight. The observations of Moreland (10) agree with ours on this point. The latest definite date recorded on specimens taken in nature is September 26.†

No data whatever, other than the records of capture of moths just discussed, have been obtained on emergence of the moths in nature. In

*Courtesy of Mr. Foster H. Benjamin.

†Koebele collection, California Academy of Sciences, by courtesy of Mr. E. P. van Duzee.

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1921 a half-dozen bags of mosquito netting 4 feet in diameter and 6 feet in depth, with iron rings bound in the openings, were inverted over six individual Thurberia plants showing bollworm infestation of the previous year. It was hoped thus to secure freshly emerged moths, but none were taken by this means, and before the season was over all the plants were destroyed by storms, floods, or cattle.

OVIPOSITION

The oviposition records of 4 years bear out even more strikingly the correlation mentioned. The eggs, though small, are white and are deposited in conspicuous positions, such that it is a simple matter for one accustomed to their appearance to find them. They are, with but very few exceptions, placed on the tips of flower bracts or on the pointed tips of the leaves of *Thurberia*, and on the upper surface. The few exceptions consist mainly of instances in which eggs are deposited on the angles caused by destruction of portions of leaves. In one lot of 164 eggs, 105, or 64 percent, were deposited on leaf-tips, and 59, or 36 percent, on bracts. In another lot of 181 eggs collected at random, 180 were on leaves and but one on a flower bract, though from the habits of the larvae, one might well expect the reverse. The earliest dates on which eggs have been found are as follows: August 17, 1921, August 18, 1922, August 14, 1923, and August 15, 1924. Pierce and Morrill (12) mention the fact that eggs are sometimes found in clusters of two, or still more rarely, three. We do not believe, however, that this is an exception to the rule of laying eggs singly. Repeated observations have shown that almost never do the eggs thus placed side-by-side hatch the same day, and it appears therefore that they were deposited singly at different times and were contiguous merely by accident. Only 10 eggs, five pairs, of the above lot of 164 were thus deposited, while of the lot of 181 eggs, only 4, two pairs, were thus placed.

The incubation period determined by various means is 6 days. On one occasion some eggs were deposited in a box containing Thurberia leaves in which several moths were held captive over-night. At other times all eggs were collected from a given plant on a certain day, and the following day eggs deposited during the intervening night were collected and kept under observation. These observations gave the same results, and are further corroborated by out-of-door records. Taking August 15 as the beginning of oviposition larvae would appear August 21, and since August 25 is the approximate date when flowering of *Thurberia* begins freely, it will be seen that oviposition is well correlated with the appearance of buds, in which the newly-hatched larvae begin to feed.

In 1924 the abnormal climatic conditions already stressed resulted

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in great irregularities in oviposition. On August 16, for example, when the first eggs were noted north of Stone Cabin Canyon a single egg was found in a certain area where none occurred the day before, indicating normal oviposition. Three quarters of a mile distant in the same wash, where there was evidence of a light, local shower, a few eggs were noted. Two and a half miles beyond this wash, nearer the mountains and at an altitude at least 400 feet above the other areas, 181 eggs were gathered on this date from a small group of plants, 32 percent of which already had hatched, indicating an abnormally early oviposition at that point. On August 19 in the Sierrita Mountains, a few miles directly across the Santa Cruz Valley and at about the same elevation, half a dozen eggs were seen in the course of inspection of some hundreds of Thurberia plants, indicating late oviposition. No such irregularities were noted in any previous year.

In the very dry area so deficient in eggs and in material for larval food in 1924, one could but wonder whether most of the moths were remaining in the pupal cells on account of the drought and whether, if so, they might issue the following year. Webb (15) shows that one of the specimens sent in 1918 to Brownsville in the pupal stage actually issued, not in 1919, as did 9 others, but on August 28, 1920, nearly 2 years after pupation.

With this indication of its resistance, and since the bollworm infestation in 1925 in this identical area appeared to be about normal, it is quite possible that some moths spent some 22 months in the pupal stage. On the slightly later dates recorded for 1921 and 1922 it may be noted that no examinations were made on the preceding 3 or 4 days and that eggs were somewhat more numerous than on the earlier dates of other years, indicating that oviposition had actually begun a little prior to the recorded dates. The beginning of oviposition, therefore, falls with surprising regularity on or very near the middle of August. At this date there is but little outward evidence that the wild cotton plants are about to bloom, though close inspection reveals the presence of some very small buds (squares). Six days later when the first larvae hatch small buds are numerous. Eggs become increasingly numerous up to the first week of September. Egg collections made in September show a rapid increase in percentage of hatched over unhatched eggs. On September 9, 1920, for example, of 164 eggs examined 66, or 40 percent, were hatched, and 98, or 60 percent unhatched. On September 16, 1921, of 100 eggs examined, 89 were hatched and 11 not hatched. Therefore, if the egg stage be 6 days, as will appear, 89 percent of the eggs laid up to September 16 had been deposited by September 10.

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RELATIVE ATTRACTIVENESS OF COTTON AND *THURBERIA*

In connection with oviposition an effort was made to determine the relative attractiveness of *Thurberia* and *Gossypium* for the female moths. Nothing is known concerning the feeding of the moths. As their life span in the moth stage is probably somewhat less than 2 months, it is possible they do not feed. Further, their daily period of activity seems to be only 3 hours or less. They are very quiet throughout the hours of daylight and must be well hidden, as the author has found but two specimens in the open by day in the course of many hours of work among Thurberia plants. Moths in the laboratory or in screen cages outside can scarcely be made to move by flight during the day. The food plant on which the eggs are laid must necessarily have an attraction for the female moths whether there be any attraction as a food or not. First attempts to test this matter as between *Thurberia* and cotton *(Gossypium)* consisted in placing moths taken at lights in a large screen cage containing both plants. The test resulted in complete failure, however, as the moths will not oviposit in confinement. Moreland (10) reports the same result. We have one doubtful record of such oviposition and that upon cotton. The egg was not discovered, but a larva was found later, the presence of which could not otherwise be satisfactorily accounted for. In 1922, 1923, and 1924 efforts were made to conduct a field test of attractiveness of cotton for oviposition. The plan was to grow a small patch of cotton located in such close proximity to infested *Thurberia* as to offer opportunity for oviposition on either. For this purpose it was necessary to have tillable soil and irrigation water as well as the continued presence of some one who could irrigate the cotton as required. The location chosen was the ranch headquarters of Wm. Nicholson in Stone Cabin Canyon of the Santa Rita Mountains, 9 miles east of Continental. This is the spot formerly known as McCleary's Camp,* Stone Cabin Canyon, so designated in much entomological literature, particularly that of Thurberia weevil and bollworm. The small plot of ground available is located on the bank of the wash, with *Thurberia* growing plentifully both upstream and downstream at distances of less than 100 yards in either direction. Moths have repeatedly been taken at night just across the wash, about 50 yards distant from the cotton patch..

In 1922, despite such care as could be given by the experimenter with headquarters 40 miles distant, cutworms and rodents destroyed two plantings. Efforts to transplant even small plants in August were unsuccessful and the test had to be abandoned for that year. In 1923 the

*This name is destined ere long to disappear from maps, and will mean nothing to coming generations of entomologists.

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early part of the season was extremely dry, following a very dry winter, and there was insufficient water for irrigation. Of the two wells available, one was totally dry, and the other barely met the demands of the livestock. Copious summer rains fell in July and August, however, and some seed was planted July 24. This germinated quickly and grew very rapidly, but was not at a stage such as could be considered to constitute a fair test when oviposition was at its height, as there were no squares on the plants during that period. In 1924 a backward crop was carried through up to the usual rainy period, which would have made a good crop had normal rains fallen. Unfortunately this proved to be an exceptionally hot and dry summer throughout and only a poor crop resulted. Squares, blooms, and bolls were present, however, during the period of oviposition for the moths. Not an egg was deposited on the cotton plants, though moths were taken at lights just across the wash, about 50 yards distant. It must be added, however, that Thurberia plants in this and other nearby washes were in extremely bad condition, not only from drought, but from browsing by livestock, and, as a consequence only a very few eggs were to be found within a half-mile or more. This condition might be expected to force oviposition on the cotton plants. The whole season was one of such great irregularity, and so few moth eggs were deposited in many areas, that it is an open question whether a normal number of imagos emerged. In the meantime, approximately an acre of cotton in good condition was being grown for weevil experimentation at Agua Caliente, 16 miles northeast of Tucson, the site of Coad's weevil experiments in 1914 (4). This is within the normal range of *Thurberia*, but one night of lantern work on August 20, did not yield any specimens. Weekly, or more frequent, inspections of this cotton throughout two seasons have shown neither eggs nor bollworm larvae. It appears unlikely, therefore, that the female of *Thurberiphaga diffusa* will voluntarily oviposit on cotton. If this be true, there is certainly little danger of natural infestation of cotton by the Thurberia bollworm, since there is practically no other conceivable means by which an infestation would occur.*

HATCHING AND LARVAL HABITS

The larva makes its way out of the egg-shell by cutting a slightly oblong hole usually in one side of the larger portion of the egg just

*After this was in type reports were received from Federal inspectors to the effect that a number of Thurberia weevil infestations have been found in the domestic cotton crop of 1925 at different points along the Santa Cruz Valley. These infestations were most marked in the upper valley between the Santa Rita and Sierrita ranges of mountains, where *Thurberia* is not far distant from the fields. It is worthy of note that thus far no Thurberia bollworm infestation has been reported.

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above the base. The egg-shell is not devoured and remains in position for a considerable period, dead white in color, and as conspicuous as ever. From known habits of the older stages it seems probable that the majority make their way out of the eggs at night. They almost invariably do so in the laboratory, though on a very few occasions they have been observed to issue by day. The complicating factors introduced by confinement in jars might easily account for this variation. Immediately on leaving the egg the larva seeks food and shelter. It works downward and inward along the leaf or stem to an axil or fork, from which point it turns upward on an exploratory tour. Should it fail to find a suitable bud, small ones being preferred, it again turns downward and repeats this method of exploration until a satisfactory bud is found. This it at once enters, usually eating its way in on the side of the bud near the base. Rarely a small boll is first attacked. Sometimes the opening is made above the edge of the close-fitting involucre, other times by piercing the latter. An angle where the bract joins, affording some measure of protection, is sometimes preferred. Invariably in the field, whether in this or a more advanced instar, the larva guards against being carried to the ground through the shedding of the injured bud or boll by providing a bond of silk at the base of the flower stalk, holding it firmly to the parent plant. An injured bud almost invariably, and injured bolls commonly, break at this joint and would fall if not thus attached. Unless it fell in the shade the high temperature then encountered on the soil surface would prove fatal to the contained larva. Soil-surface temperatures reached 158° F. in southern Arizona in the summer of 1925 as shown by a recording soil thermograph. In 1924 a soil-surface temperature of 181° F. was taken in June with a reliable thermometer. A heavily infested plant is readily discernible at some distance owing to the numerous pendent buds and bolls, hanging by this silken anchor (Fig. 5). The bollworm sometimes spins silk about and over the bud, if the latter is nearly ready to open, and thus prevents the flower from opening. It is believed that normally the anchor silk is spun by the larva before entering the bud, though cage observations on larvae removed from their shelter in daytime and thus compelled to seek a fresh bud or boll by day sometimes show an interesting variation. In such cases the larva may be in such haste to get under cover that this precaution is neglected, but in most cases it will be found later that the larva has issued from its retreat under cover of darkness and has spun the usual anchor. No larva has ever been observed abroad on the plant by day, though, as will be shown, each consumes a number of buds and bolls. The change from one to another normally takes place during hours of darkness. The distance traversed by a newly hatched

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larva from the egg to the bud finally selected has been observed to be as much as 2 feet, but this does not indicate how many unsuccessful side trips may have been made before a suitable location was found. The entrance hole is usually left open and from it is ejected a yellowish frass. One small bud from 1/8 to 3/16 of an inch in diameter generally suffices for the first instar which extends over but 2 days,—sometimes 3 days in the laboratory. The first molt then occurs within the

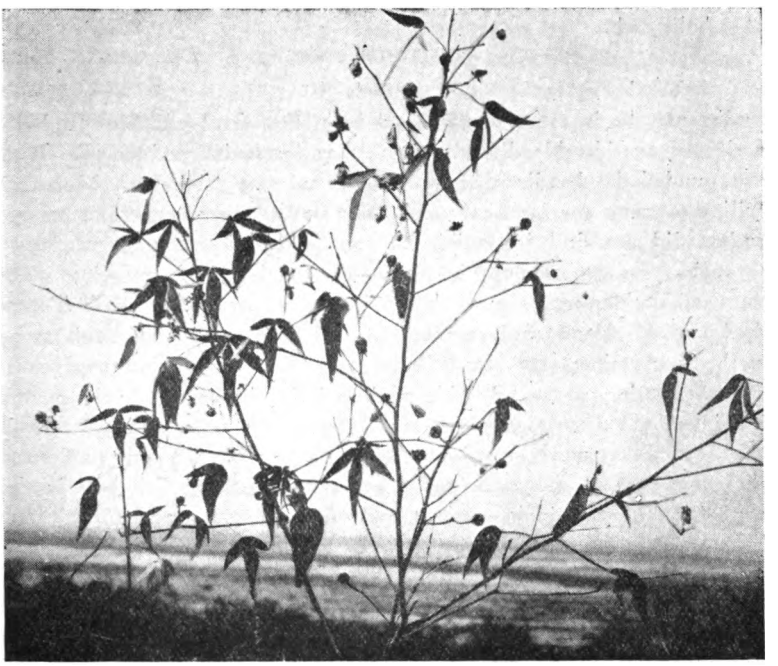

Fig. 5.—Portion of Thurberia plant showing numerous infested buds and bolls hanging by the silken anchors woven by the attacking bollworms as a safety measure.

now hollowed bud, after completion of which the larva makes its way to a fresh bud or small boll. Only rarely does a newly hatched larva attack a boll and then only a small and tender one. It could not be ascertained that there was any definite stage or instar at which the preference of the larva changes from buds to bolls. From one to four buds of various sizes may be successively attacked before selecting a boll, and occasionally a larva has been recorded as returning to buds after having eaten out a boll. Occasionally an entrance hole is partially closed with a web of silk, and the larva in this case is likely to be found parasitized,

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but we are not able to say that this is uniformly true. Such closing may in some cases be for better protection while molting, but it is not a regular practice. The bolls attacked are as a rule completely hollowed out. The average number of buds and bolls of *Thurberia* consumed by nine larvae successfully carried through the larval stages in 1923 was 3.4 buds and 4.1 bolls. In 1922, ten larvae carried through the bud-feeding stage consumed an average of 3.5 buds each, while five larvae recorded through the further stages of boll feeding consumed an average of 6 bolls each.

METHODS USED

A brief description of the methods of conducting the life history studies may be in order, inasmuch as both Townsend and Moreland experienced considerable difficulty in rearing larvae in confinement. Both were under the handicap of working in a camp laboratory, Moreland failing to carry any larvae through from egg to pupation. The present author did not find it possible to carry a large percentage of larvae through from egg to pupa in confinement and at the same time make the examinations necessary to determine instars accurately. Both Townsend and Moreland used tumblers or jelly glasses supplied with moist earth, as containers for the bolls with feeding larvae, and used cloth as a ventilating cover. By this method it is difficult to supply correct humidity, and dissatisfied larvae can cut their way out through the cloth covering. Too much ventilation keeps the air dry enough to destroy the succulence of the food, unless an excess of moisture is kept in the earth. After testing moist earth, a wad of moist cotton, and fresh Thurberia leaves, as sources of moisture in a closed tumbler, it was determined that leaves were most suitable. Jelly tumblers of low or bowl form with tight-fitting covers were used. In one of these were placed a number of eggs with several small buds of *Thurberia*. The next morning all were removed, hatched eggs were discarded, the bowl cleaned, unhatched eggs, fresh buds, and leaves being replaced in the jar. Each bud infested by a newly hatched larva was then isolated in a jelly glass with one or two fresh Thurberia leaves to supply moisture. After experience had shown at about what period the larva would likely seek fresh food, fresh buds or bolls were also placed in the tumbler when changes were expected and the old one was discarded after the larva had transferred. In case of removal of a larva from the boll for examination it was simply placed with fresh food and leaves. This method has the advantage that the entire contents of the tumbler can be removed daily, the jar cleaned, and material entirely fresh with exception of the infested boll put in. Determination of instars depended upon inspection of larvae by partial or complete opening of buds and bolls, and

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search in the refuse of abandoned buds and bolls for cast-off head capsules.

An abundance of *Thurberia* growing in both screened and introduction gardens supplied fresh food and also gave opportunity for observation of larval habits and life history on growing plants out-of-doors, but under protection of screen. By means of tests under screen it was found possible to infest these plants by placing upon them eggs of *Thurberiphaga* collected in the mountains. The method used succesfully was to collect portions of Thurberia leaves bearing eggs, and then to glue these portions to leaves of Thurberia plants under screen. Thus were obtained data corroborative and corrective of findings in the laboratory.

Under screen protection there was available also a supply of cotton being grown by the Plant Breeding Section. Beginning on cotton plants doubly screened, larvae well advanced in growth (probably mostly third instar) were placed on bolls. These larvae would attack and enter the cotton buds or bolls without hesitation, especially if they were placed within the bracts. If placed on the plants to shift for themselves they were somewhat baffled by the relatively complete enclosure of the boll by the large bracts. It was found that such larvae completed their larval growth in apparently normal fashion on cotton. With but a single exception, however, all bollworms thus completing their growth perished sometime between abandonment of the bolls for pupation and the normal time for emergence the following year. Whether or not this was due to irrigation which was rather frequent in the screened garden, undoubtedly resulting in the maintenance of a much greater degree of soil moisture than is normal to the sandy or gravelly, well-drained soils in which *Thurberia* grows, we attempted to test by another series of experiments. Three screen cages were provided, one inside the irrigated screened garden, another in the more heavily irrigated introduction garden, and a third on well-drained, gravelly, mesa soil where there was no irrigation and which was the nearest approach to the soil-habitat conditions of *Thurberia* afforded by the University Campus. In the season of 1921 many larvae that were seeking the soil for pupation were placed individually in small (2-inch) flower pots of fresh earth. Of these some died without entering the soil, some —too far advanced—pupated on the surface and a total of 38 entered the soil at once and presumably pupated. Three additional larvae spinning for pupation within old bolls were buried in soil in pots. These 41 pots were buried flush with the earth in the three cages as follows: Pots 1-10 on October 8 and pots 21-25 on October 10 in cage in introduction garden; pots 11-20 on October 8 and pots 26-30 on October 10 in cage within screened garden; pots 31-41 on November 26 in

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cage on mesa soil. It may be stated that in several instances the earth was carefully poured from the pots before they were buried and pupal cocoons found on the bottoms or sides of pots. A complete record of subsequent irrigations in the screened garden was not secured for the autumn months, but from February 16 to August 5, 1922, the garden was irrigated 14 times in addition to the natural precipitation. The irrigation record for the introduction garden was carried away, but the number of floodings would approximate a half-dozen. On the mesa soil a total precipitation of 6.91 inches was recorded from November 1, 1921, to July 31, 1922. Not one moth emerged from the cage on mesa soil, nor from the cage in the introduction garden. A single moth emerged in the screened-garden cage on September 4, 1922. Since all specimens perished in the other cages, and all but one in this cage, no conclusions concerning the effect of irrigation can be drawn. Since, on the other hand, in the latter cage one larva passed its entire life from egg to abandonment of the boll, and probably pupated normally in the soil, it is assumed to be most likely that this one emergence was from that normal pupation and that all in the flower pots perished. On September 23-25, 1922, all pots were taken up and the soil was examined to determine the fate of the pupae if possible. Pupae or cocoons were not found in all pots, possibly indicating death of larvae before pupation. Many were found, however, in such a state of disintegration as to indicate they had died in the early months of the pupal period, while in four pots from the screened garden, remains of four fully-formed moths with typical colors of the adult were found.

A repetition of essentially this experiment, but omitting the use of flower pots, allowing the larvae to enter the soil of the cages directly, will be described below. In the meantime other developments of the problem appeared to indicate that this insect might have less dangerous potentialities than had been supposed, and the attempt to determine whether irrigation would have a deleterious effect was postponed.

In early September, 1922, seven newly hatched larvae were confined with squares of cotton. Only one of these succeeded in entering a bud, and none survived. The one entered a very small square but on the next day was found dead in the jar, having only partially eaten the bud attacked. Failure to gain access to the buds may have been due to two factors; first, the pubescence of the cotton squares, and second, the relatively complete enclosure of the bud within the bracts. Thurberia buds are free from pubescence and the bracts are slender and in no sense enclose the buds. There is no point to calling them squares except by transfer of the term from cotton to a corresponding stage of the Thurberia bud. Actual observation of newly-hatched bollworms on

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the cotton squares showed that the pubescence offered a real obstacle to them.

Following this lead 100 eggs of *Thurberiphaga* were placed on cotton in the screened garden, it being felt now that the losses due to difficulty of entering the buds and to irrigation, cultivation, and unknown factors resulting in failure of moths to emerge in the cages rendered such a proceeding relatively safe. These eggs were attached in the manner above described and found satisfactory on *Thurberia*. No infestation whatever was detected as a result of this experiment in placing eggs of the bollworm moth on cotton. Following this, on September 29 a large number of bollworms in advanced stage of growth was collected in the Santa Rita Mountains. These were taken to the laboratory and sorted, those showing a desire to burrow being placed on the soil in the three cages and in the screened garden outside the small cage. Altogether, with mature larvae from indoor rearings, the number in each cage supposed to have entered the soil for pupation was 25, while approximately 46 entered the soil of the screened garden.

This planting was extended over 10 days from September 25 to October 5, the greatest number on September 30. Here again results were negative. Not a single moth emerged in 1923 from this "planting" of larvae. Had moths issued in the screened garden another test of choice between *Thurberia* and cotton might have resulted, since both plants were growing therein. Eight more moths from the mountains, not sexed, but known to have at least one female because of oviposition in confinement, were loosed on August 15, 1923, in the screened garden, not within the small cage, and all disappeared without a single egg being deposited.

The placing of eggs on cotton was repeated as follows: September 7, 1923, 75 eggs; August 24, 1924, 50 eggs; August 25, 1924, 50 eggs; September 5, 1925, 115 eggs. Thus in 4 years 390 eggs of *Thurberiphaga* have been placed on cotton in a manner proved satisfactory for transplanting eggs to *Thurberia* in the cages, and not one infestation has been found resulting.

In the meantime further laboratory tests were conducted, especially in 1924, with tame cotton squares and newly hatched bollworms. In jelly tumblers with hatching eggs were placed cotton squares but not *Thurberia*, so the hatching larvae were close to the only available food supply, which they must enter or perish. Of 27 larvae thus hatched, only four entered cotton buds. Of these one lived but 2 days, two others each lived 3 days, and the fourth lived 16 days. Why it then perished is not known. Larvae of its size transferred from *Thurberia* to cotton have an excellent chance of survival. Twenty-three of the

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twenty-seven died without entering a bud, one of them lying entangled in the pubescence. It seems safe, therefore, to conclude that infestation of cotton by *Thurberiphaga diffusa* is only a remote possibility, since practically the only method by which it might occur in the field would be through direct oviposition on cotton and subsequent infestation by the newly hatched larvae. Oviposition on cotton is believed to be unlikely, while it appears still less probable that infestation would follow if such oviposition occurred. The possibility of Pima cotton or other less pubescent varieties becoming infested is somewhat less remote than the infestation of the more densely pubescent varieties.

SUMMARY AND CONCLUSIONS

1. *Thurberia thespesioides*, so-called "wild cotton," in the mountains of southern Arizona, is commonly infested with the larvae of a Noctuid moth, *Thurberiphaga diffusa* Barnes, destructive to the buds and bolls of the plant. This insect is called in this paper the Thurberia bollworm.

2. The entire life history has been worked out. The insect is closely restricted to *Thurberia* as a food plant.

3. It has been suggested by several entomologists that this bollworm might readily transfer to cotton grown in valleys near the habitat of *Thurberia*, and thence become a destructive pest of cotton.

4. Experiments have been conducted to determine its potentialities as a cotton pest.

5. The insect is active only about two months of the year, early August to early October. It remains approximately ten months in pupal cocoons in the soil.

6. Its life history shows a striking correlation with the normal fruiting habit of *Thurberia*.

7. Moths would not oviposit on either cotton or *Thurberia* under screen. In the outdoor tests conducted the moths did not oviposit on cotton. Owing to conditions beyond control these tests were not wholly satisfactory.

8. Eggs transferred from *Thurberia* in the open to the same plant under screen resulted in normal infestations, but 390 eggs thus transferred to cotton gave no infestation.

9. Larvae in advanced instars will finish their feeding on cotton as a food plant, but there is no means by which such transfers are likely to occur in nature.

10. It is concluded that the Thurberia bollworm is not a potential pest of cotton, and that its continued presence in *Thurberia* need not give cotton growers concern.

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A STUDY OF THE COLORADO RIVER SILT

GIFT
JUL 26 1926

By J. F. Breazeale

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FOREWORD

From an economic standpoint, the Colorado River is probably the most valuable single asset that is possessed by the Great Southwest. The quality of its water is excellent, and the flow, if properly directed, is sufficient to irrigate and to bring under cultivation, at least 3,000,000 acres of desert land. However, the river carries an enormous amount of silt and clay.

Up to the present time, very few of the potential possibilities of the river have been utilized. There is already abundant evidence to the effect that the handling of this silty water presents difficulties that will, in the future, tax the ingenuity of irrigation engineers. The silt collects in the canals and must be removed by expensive methods; it builds up the soils under irrigation, especially at the upper ends of the borders, at a rapid rate, so that the land constantly requires releveling; eventually it will raise the level of the land so high that it cannot be reached by gravity water. Last, but not least, the silt covers the soil as a slightly permeable layer or blanket, in varying thicknesses. This, at first, upon sandy soils, may be beneficial, but as the silt blanket accumulates, it soon becomes so thick as to make cultivation very difficult and the penetration of water exceedingly slow.

From the indications upon lands in the lower Colorado basin around Yuma, which have been under irrigation only about twenty years, it is evident that some practical method of handling the silt must be found before a permanent irrigation agriculture can be established in this valley. It will never be possible to desilt the water completely, but some method of treating the silt in order to flocculate and render it more permeable, is quite possible. These facts show the need of research work upon the transportation and deposition of silt, for in great undertakings of this kind an intelligent working hypothesis is the first essential.

For many years irrigation engineers have been studying the silt-carrying capacities of streams from the standpoint of the velocity of the currents, and similar physical factors, but the relationship of the quality or chemical composition of water to the quantity of silt that a stream may carry, apparently has been largely overlooked.

Soils are either flocculated or deflocculated depending upon whether or not sodium, in replaceable form, is present in the soil zeolites. Soils whose zeolites are completely satisfied with calcium, and contain no replaceable sodium (normal soils), are flocculated. They take water readily and, if shaken with a large volume of water, settle quickly. On the other hand, soils containing basic sodium compounds or sodium zeolites

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are deflocculated. They are impervious to water and, if shaken with an excess of it, do not settle out, but remain in suspension almost indefinitely. Thus, irrigation waters that contain an excess of soluble calcium flocculate the soils to which they may be applied, while "soft" waters (those containing basic sodium compounds in solution) deflocculate and disperse soils to which they may be added.

The data presented in this bulletin show that soil dispersion and silt (or clay) transportation by streams are closely allied phenomena, and that oftentimes the solutes present in the water of a stream exert as great an influence upon its silt-carrying capacity as do the velocity of the current and other physical factors.

This bulletin is the result of a rather extensive series of silt and soil studies with Colorado River water, which have been carried on in the Agricultural Chemistry laboratories of the University of Arizona during the past 2½ years. This work shows the necessity of such studies where heavy silt loads are encountered in streams to be used for irrigation purposes.

PAUL S. BURGESS,
Agricultural Chemist.

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A STUDY OF THE COLORADO RIVER SILT

By J. F. Breazeale

INTRODUCTION

The term silt, as applied to the sediment that is carried in suspension by the water of the Colorado River, must not be misunderstood. The sediment is not true silt, but consists mainly of clay particles so finely divided at times as to be partly colloidal. The term silt, however, will be used in this discussion.

The Colorado River is nearly always muddy. The silt in the water as it comes into the lateral irrigation ditches at the Yuma Experiment Station Farm, varies from about 2 percent during certain flood times, to about .01 percent or less, at extreme low water. It will be seen that an enormous amount of silt is thus brought down annually and spread out upon the land under irrigation. The total amount of silt that is brought down annually by the river has been estimated by many investigators. Forbes, for example, in 1900, determined the amount to be in the neighborhood of 61,000,000 tons, or enough to make 53 square miles of alluvial soil 1 foot deep.*

When sandy soils are first placed under irrigation, the addition of this silt is beneficial, but the time may come when the percentage of sediment may reach a point where it is injurious to the soil. The silt also clogs the irrigation ditches, and hence entails considerable expense to farmers. In many other ways the silt offers serious problems to the irrigation engineer.

The alluvial lands in the lower Yuma Valley of Arizona, and a great area in the Imperial Valley of California, were formed during past ages by the silt that was brought down by the Colorado and Gila rivers. The Gila, however, flows in appreciable amounts at flood times only, and the total amount of silt that is brought down by this river is small in comparison with that brought down by the Colorado. We can safely assume that most of the soil of these two valleys was brought down by the Colorado River.

The Colorado, in its upper basin, receives the drainage of the Grand and the Green rivers and of many smaller streams. During the winter months this mountainous territory is covered with snow and there is little runoff, but in the spring the snow melts and a great volume of flood water comes down the river bringing with it the sediment that it has eroded from the mountain canyons. About the time that the flood

*Ariz. Agri. Exper. Sta. Bull. No. 44: River Irrigating Waters of Arizona, their Character and Effects, R. H. Forbes, 1902.

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waters from the northern drainage basin begin to subside, the summer rains in northern Arizona and New Mexico commence, and periodic floods are again poured into the Colorado from the San Juan and the Little Colorado rivers. These bring with them the sediments that have been eroded from the bad-lands and from the Painted Desert in their basins. At Yuma, Arizona, the Colorado is joined by the Gila, which is sometimes referred to as the "muddiest stream in the world," but except at very high water, it seldom reaches the Colorado with its silt load.

It will thus be seen that the Colorado River silt is derived either from the canyon country far to the north, or from the bad-lands and painted deserts of the south. In either case, especially the latter, the soil from which the silt is derived might be expected to be colloidal and dispersed.

The soils of the lower basin of the Colorado are often deflocculated or dispersed. The fresh silt that is now being brought down and spread out over the land or deposited along the irrigation ditches, is badly dispersed. However, if a large amount of gypsum is added to the dispersed soils of the valley, they become flocculated, and if gypsum is added to the muddy waters of the Colorado, the silt is also flocculated and it will settle readily. It is reasonable to assume, therefore, that if the river itself had a sufficient amount of gypsum in solution, the silt would be flocculated and would not be carried in suspension. In such a case the river would either never pick up its load or else the silt would be deposited at its head waters or at places along the course where the speed of the current is appreciably checked.

In many ways the Colorado River silt, as it is delivered in the lower basin, shows signs of being dispersed, that is, the colloidal particles seem to be carrying negative charges. When the dry silt is shaken with water, it will remain suspended and usually will not settle for a long time. If pure water is used, the solution will show a pink color upon the addition of phenolphthalein, indicating the presence of an excess of hydroxyl ions. When the silt is purified by repeated washings with distilled water, and then shaken with pure water it will continue to give an alkaline reaction with phenolphthalein. When the silt is obtained dry, and treated with a strong solution of gypsum, it is flocculated and settles rapidly, but when the excess of gypsum is removed by repeated washings, the silt will again become dispersed, and will give an alkaline reaction with phenolphthalein in much the same way as did the untreated silt. It must be remembered that the silt was transported a long distance in, and was laid down from the Colorado River water, which, during a greater part of the year, contains an excess of gypsum. The dry silt upon washing, gives a filtrate that contains some gypsum, yet the silt, when shaken with pure water, gives a solution that contains an appreciable amount of hydroxyl ions. The silt, it is true, contains

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some calcium and, in the absence of carbon dioxide, this would give some hydroxyl ions to the solution. There is every indication, however, that the solutions of the silt in distilled water contain hydroxyl ions that are associated with sodium ions. Dr. Paul S. Burgess, in his work with the soils that have been deposited upon the Yuma Mesa, has found this to be the case.

The silt as it appears in the irrigation ditches in the lower Colorado basin is certainly dispersed, and this dispersion has been brought about largely by the following factors: First, the soil from which the silt is derived, as it exists *in situ* upon the northern plateaus is colloidal and dispersed, no change having been brought about in its condition by the water in the course of its transportation; and second, the silt is originally flocculated, but at times the quality of the water is such as to bring about deflocculation.

THE SILT-CARRYING CAPACITY OF A RIVER AS INFLUENCED BY COLLOIDAL DISPERSION

The current of the Colorado River is rapid, and this is a great factor in the movement of silt, but there are other factors in this silt movement that seem to be associated with colloidal dispersion. The silt-carrying capacity of a stream is determined largely by the velocity of the current at the slowest point in its course. If the velocity of the current is doubled, its silt-carrying capacity is multiplied by 32, while the maximum size of the particles that may be removed by the current is multiplied by 64. Doubling the velocity of the stream would be equivalent to dividing the silt particles into 64 parts. When clays are flocculated, the individual particles are fairly large, but when the same clays are dispersed each particle splits into a great number of other particles, sometimes so small as to be colloidal. A colloidal particle may be as small as one-millionth of a millimeter in diameter, so it is evident that the division brought about by dispersion may be infinitely great. In many instances, therefore, the size of the particle may amount to a great deal more than the speed of the current, in the consideration of the silt-carrying capacity of the stream.

CLASSIFICATION OF THE SILT LOAD

According to Mr. Porter J. Preston, Superintendent of the Yuma Irrigation Project, the material that is carried by the Colorado River may be divided into two classes: First, the bed-load, or that part of the silt that tends to settle readily, or to move with the lower strata of water; and, second, the suspended load, or that part of the silt that does not settle rapidly when the velocity of the current is checked.

The speed of settling of silt is a good index of its state of dispersion, the greater the dispersion the more slowly the silt will settle. The

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heavier part of the bed-load may be only slightly dispersed or it may even be flocculated, while the suspended load may be highly dispersed. The suspended load is the silt that usually gets into the irrigation laterals, and is of the most concern to the farmers.

If a river is flowing at a certain velocity, with a maximum load of suspended silt, a slight change in the velocity of the water may occur that may precipitate a part of the suspended material which will then settle and the river may thereafter carry only a fraction of a load. The reverse of this also is true, the river may be carrying only one-half of a suspended load, and one-half of a bed-load, and a change in the quality of the water may bring about a partial dispersion of the bed-load which may convert it into a suspended load. Even if the velocity of the river is maintained at a fixed rate, there is no doubt a constant adjustment between the bed and the suspended loads.

Dispersion is concerned with the reduction of the size of particles, and the size of particles is of the utmost consideration in the transportation and redeposition of silt.

THE DISPERSION OF SOIL COLLOIDS

The silt as it floats in the Colorado River is soil in motion, and no doubt it possesses many of the properties that it originally had before it was disturbed by erosion upon the high plateaus of Colorado, Utah, and Wyoming, or upon the desert bad-lands of northern Arizona and New Mexico. In a soil, the clay fraction is composed largely of hydrated silicates, or alumino-silicates, in combination with either the bases calcium and magnesium on the one hand, or sodium and potassium on the other. For want of a better name, these silicates are termed zeolites.

In a normal and neutral soil, the zeolites exist as calcium and magnesium compounds, and such soils are usually flocculated and will take water readily. If such soils are lifted by moving water they will settle rapidly, and will not be transported a long distance, except when the water is moving swiftly. If, however, the zeolites exist in combination with sodium or potassium, the soils or clays are deflocculated, and are usually impermeable or slightly permeable to water. When lifted by water such soils disperse themselves in the solution, settle very slowly, and may be transported long distances.

One of the distinctive features of these soil-zeolites is that the bases calcium, magnesium, sodium, and potassium, are easily replaced one by the other. If a flocculated and permeable soil, containing calcium zeolite, is leached with a solution containing any soluble sodium salt, sodium chloride for example, the calcium is replaced and becomes calcium chloride, and is leached out, while the sodium enters into combination with the silicate and remains in the soil. Under such conditions the soil may

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become impermeable and dispersed. If the soil is now treated with a solution of calcium sulphate, the sodium in turn is replaced by the calcium, and the soil will become flocculated and permeable. Such an exchange of bases may be continued indefinitely.

Most western soils, at one time or another, have come in contact with either sodium chloride or sodium sulphate. These salts have replaced the calcium and magnesium and the zeolites now exist as sodium salts. As long as an excess of a soluble sodium salt is present, the soil will remain flocculated, but upon leaching with pure water, rain, or melted snow, the soils become dispersed.

Let us assume that such soils that have been leached with pure water until they are practically free from soluble salts, and have become dispersed, are lifted by rapidly moving water, and are brought into the river channel as silt.

Like all other chemical reactions the exchange of bases in zeolites is influenced by the concentration of the leaching solution. The stronger the solution, the more rapid and the more effective will be the replacement. When the dispersed silt, containing sodium zeolite, reaches the main channel of the Colorado River, it comes in contact with calcium, in amounts that vary with the floods. If the concentration of calcium is relatively high, the reaction upon the sodium zeolite may be pronounced, and the sodium may be largely replaced by the calcium. If, however, the concentration of calcium in the river is low, very little replacement of the sodium in the zeolite may be expected. So it seems that the replacement of the sodium ions in the zeolites of the dispersed silts, and their consequent precipitation is largely a function of the concentration of calcium in the solutions.

But the sodium zeolites are only slightly soluble in water, and in all probability the replacement of the sodium ion by calcium will go so far and no farther, and that, even though the concentration of calcium in the river water is at its highest, a small amount of sodium zeolite will still remain in the silt. If base replacement is an ordinary chemical reaction, as it seems to be, the reaction between calcium and sodium can go no farther than that represented by the ionization of the sodium zeolite. If the ionization of the zeolite is checked, or forced back, by any other salt in the solution, the ionized sodium zeolite is, for the time being, insoluble and inert, and the dispersed silt may be flocculated, and become either a bed-load or be dropped from suspension altogether. If, however, the salt that is forcing back the ionization is removed from solution or if its concentration is decreased by dilution, as in the Colorado River at flood time, the sodium zeolite will again hydrolize and ionize, manifest itself as a dispersed colloid, and become a suspended load of silt.

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The phenomenon above described is shown in the treatment of the silt in the laboratory. When flocculated with a strong solution of calcium sulphate and washed with distilled water until free from sulphates, the silt will again become deflocculated, and will give an alkaline reaction if an excessive amount of water is added to it.

Any salt that tends to prevent the hydrolysis of the alkaline sodium salts, sodium carbonate and the sodium zeolites, and their subsequent ionization, will also tend to prevent soil dispersion. The Colorado River water sometimes contains considerable amounts of sodium sulphate and sodium chloride. These salts tend to flocculate silt, and their action will be discussed later, but it may be said here, that, in the case of these two sodium salts, the flocculating effect probably is partly brought about by the introduction of a common ion, Na, in the solution, in a concentration sufficient to force back the ionization of a less soluble sodium salt, sodium zeolite. The relative insolubility of the sodium zeolite, and the small amount of the ionized product necessary in the solution for the dispersion of the colloids, seems to indicate that this forcing back process may be a relatively easy task. There are other reasons for the flocculation of colloids that are not at all well understood.

REPLACEABLE BASES IN COLORADO RIVER SILT

The silt, as it is deposited in the lower basin of the Colorado, is a mixture of material coming from many sources, and no definite composition can be attributed to it. From a practical standpoint, however, the mixture has a fairly definite behavior, and the following measurements of its replaceable bases may be considered as representative.

One hundred grams of dry silt were shaken with 1000 c.c. of carbon-dioxide-free water, and the mixture allowed to come to equilibrium. The solution upon analysis was found to contain a total amount of .023 gram of calcium, and no magnesium. This amount of calcium represents the soluble salts in the solution and not the replaceable salts in the silt.

A large sample of silt was washed with distilled water until practically free from all soluble salts, sodium chloride, sodium sulphate, calcium sulphate, etc. The silt was dried and finely ground. One hundred grams of the silt were shaken with 1000 c.c. of saturated solution of gypsum and the mixture was allowed to stand until the silt settled. The silt was flocculated by the gypsum.

Upon analysis it was found that a total of .0430 gram of magnesium, and a total of .0315 gram of sodium and potassium (figured as sodium) had been replaced by the calcium, and had appeared in the solution.

One hundred grams of the washed silt were shaken with 1000 c.c.

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of one-tenth normal solution of barium chloride, and the solution analyzed for the bases replaced. A total of .200 gram of calcium, .050 gram of magnesium, and .0251 gram of sodium and potassium (figured as sodium) was found in solution.

A high percentage of replaceable calcium was expected, as the river water contains gypsum, and this no doubt replaces a larger part of the sodium in the zeolites before the silt is deposited. No magnesium appeared in the water extract of the untreated silt, but, when the washed silt was extracted with a saturated solution of gypsum, 100 grams of silt yielded .0430 gram of magnesium. An equivalent amount of calcium was removed from the solution and was fixed by the soil.

The most interesting feature of these determinations, however, is the fact that the washed silt contains an appreciable amount of replaceable sodium. This replaceable sodium is the sodium that exists in combination as a zeolite, and it is the sodium zeolite that is dispersing the silt. The Colorado River silt, although it floats in suspension in a gypsum solution, contains an appreciable amount of sodium that has not been replaced by the calcium that is carried in the water.

PHYSICAL CHARACTER OF THE SOIL

According to Forbes, the silt that is brought down from the mountainous country by the spring floods is reddish-gray in color, while that brought down by the San Juan and Little Colorado rivers contains yellow and red material. We are told that the Painted Desert shows all the colors of the spectrum except green. The character of the silt used in this replacement work indicated its origin to be in the northern part of Arizona or New Mexico.

A set of soil samples was obtained recently from different depths in Chaco Canyon, New Mexico, and determinations of replaceable calcium and replaceable sodium were made upon them. The canyon drains into the San Juan, and its erosion furnishes a part of the silt that in the late summer appears in the lower basin of the Colorado.

TABLE NO. I.—TOTAL GRAMS OF REPLACEABLE CALCIUM, AND REPLACEABLE SODIUM IN 100 GRAMS CHACO CANYON SOIL.

No.	Replaceable calcium	Replaceable sodium
1.	.447 gram	.1380 gram
2.	.314 gram	.0747 gram
3.	.355 gram	.0747 gram
4.	.425 gram	.0368 gram
5.	.464 gram	.0770 gram
6.	.527 gram	.0563 gram

These soils were badly dispersed, were almost impermeable to water, and when shaken with distilled water, the finer particles remained in

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suspension for weeks. It will be seen that the soils contain a relatively high percentage of replaceable calcium and a considerable amount of replaceable sodium. In many ways these soils had characters that were analagous to the Colorado River silt. All the soils contained a small amount of calcium carbonate. One would judge from their chemical composition and physical characters that they had probably originally been normal soils, or soils that contained only calcium zeolites, but that they had at some time come in contact with sodium chloride or sodium sulphate, which had replaced with sodium much, if not all, of the calcium in the zeolite. The soils then were probably leached with fairly pure water, or eroded and redeposited by pure or rain water, and the sodium salts, sodium chloride, and sodium sulphate removed. Upon removal of the soluble sodium salts, the sodium zeolite began to hydrolyze, and a part of the sodium ions was removed by leaching. As fast as a sodium ion was thus removed, a calcium ion from the slightly soluble calcium carbonate took its place, and this reaction proceeded until the impermeability of the soil that was brought about by this reaction practically put a stop to the penetration of water, and, of course, put an end to the replacement process. The author has shown that in the black alkali soils of the Rillito Valley, near Tucson, Arizona, the above described reaction between sodium zeolites and calcium carbonate does take place. It has also been shown that the most dispersed soils are usually those that contain a relatively small amount of replaceable sodium and a large excess of replaceable calcium.

It has been the experience of Mr. Porter J. Preston, that, when certain tributaries of the Colorado, particularly the San Juan and Little Colorado, are in flood, the silt is brought down in greater amounts than at other times, and that this silt settles less rapidly than does that brought down when the Grand and Green rivers are in flood. This is no doubt due largely to the fact that the floods of the Grand and Green are caused by melting snow, while the floods of the San Juan and Little Colorado are caused by torrential rains upon desert bad-lands. The melting of snow is a relatively slow process and the soils in the mountainous country are better protected by vegetation, are probably not so badly dispersed, and are not so easily eroded as are those of the bad-lands. Aside from the influence of the quality of the Colorado River water at different periods of the year, as will be discussed later, the settling power of these two kinds of silt is inherent in the character of the soils before they were eroded. The silt, derived from such soils as those from Chaco Canyon, will never settle readily unless it comes in contact with some flocculating agent. Such silt has been eroded and redeposited probably many times before it is finally taken up for its journey down the Colorado.

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The presence of growing vegetation has a tendency to keep the soil flocculated and open. Any kind of organic matter in the soil, and an active bacterial growth have the same effect. Barren soils are often dispersed. The origin of much of the silt in the Colorado River is from an area that has little or no vegetable cover, an area that is barren, and one that for ages has been subjected to leaching with pure or rain water.

If two different kinds of silts, one from the mountainous country, and the other from the bad-lands, were eroded by the same kind of water, and both were subjected to the action of the same water in the river in transit, they would probably settle, not with the same but with almost equal rapidity, but the quality of the water in the river changes with the flood, and the concentration and quality of salts in solution depend upon whether the water comes from pure mountain streams or from alkaline desert flats.

QUALITY OF THE COLORADO RIVER WATER

During the year, the total salt content of the Colorado River water varies from about 200 parts per million during the high floods of May and June, to about 1500 parts per million at low water in February and March. The calcium content varies from about 30 to 175 parts per million, while the sulphate (SO_4) varies from about 85 to 600 parts per million. It is a significant fact that when the calcium content is highest, the river carries very little silt, and that when the calcium content is lowest the river carries a heavy load. While this may be due largely to the increase in velocity at flood time, and to other physical factors, the quality of the water certainly plays an important part in the movement of the silt.

The Colorado River water is usually classified as a gypsum water, that is, it is supposed to have a permanent hardness. This is true for the greater part of the year but, contrary to the general belief, it does not always carry an excess of gypsum, but it may be neutral or it may even carry a slight excess of black alkali.* An average of three weekly analyses, made during a high flood, June 25, July 2, and July 8, 1923, is given in Table No. II.

TABLE No. II.—ANALYSIS OF COLORADO RIVER WATER DURING SUMMER FLOOD.

Total soluble salts	306 parts per million
Calcium (Ca)	38 parts per million
Magnesium (Mg)	8 parts per million
Carbonates (Co_3)	Trace
Bicarbonates (HCO_3)	168 parts per million
Chlorine (Cl)	42 parts per million
Sulphates (SO_4)	84 parts per million
Silt	2300 parts per million

*Ariz. Agri. Exper. Sta. Bull. No. 44: River Irrigating Waters of Arizona, their Character and Effects, R. H. Forbes, 1902.

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When water containing such a mixture of salts is evaporated, the calcium and magnesium in solution unite with the carbonate or bicarbonate, and precipitate out as calcium and magnesium carbonates. If the calcium and magnesium exist in excess of the amount required to precipitate fully the carbonate, the remaining calcium will unite with some other acid radical, So_4 for example, and then become calcium sulphate. A water with an excess of calcium and magnesium over the carbonates is said to have a permanent hardness.

But the percentage of gypsum does not represent the only active form of calcium. Nearly all the western, upland soils are calcareous. Calcium carbonate is only slightly soluble in water, but the presence of carbon dioxide increases its solubility greatly, so in the rivers of the West, we always have a certain amount of calcium appearing in solution as calcium bicarbonate. Upon evaporation this calcium gives up its carbon dioxide and goes out of solution as calcium carbonate. The same phenomenon is true with magnesium.

A water containing calcium and magnesium as bicarbonates, is said to have a temporary hardness. The calcium and magnesium that exist as bicarbonates are just as effective in replacing the sodium in the zeolites, that is, in flocculating colloids, as an equal concentration of calcium sulphate or magnesium sulphate, but the bicarbonates have no effect in neutralizing sodium carbonate or black alkali.

If, upon evaporation, a water does not contain enough of calcium and magnesium to neutralize all the carbonates, there will be some carbonate ions left in solution and these will come out, as evaporation proceeds, as sodium and potassium carbonates. Such a water is said to be soft, that is, it contains black alkali. The calcium and magnesium content of the Colorado River water during the period represented in Table No. II, was 38 parts per million of calcium, and 8 parts per million of magnesium. This was sufficient to neutralize only 156 out of 168 parts per million of bicarbonates, which left a small amount, 12 parts per million, of HCO_3 in solution. These analyses represent the quality of the Colorado River water at Laguna Dam, and before it was mixed with the water of the Gila River.

The amount of black alkali that was contained in the water during this flood period was very small, it is true, but it is well known that an exceedingly small amount of black alkali may cause the dispersion of colloids. At every summer flood, the amount of calcium in solution gets very low, 40 to 60 parts per million, and during each of these periods the river water contains very little, if any, calcium in excess of the amount necessary to precipitate the carbonates, that is, the water at these periods has little temporary hardness and little or no permanent hardness. The silt-load of the river at this flood is usually not very

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great, but the water probably carries a greater part of the silt that was eroded, yet this may not be nearly enough to make a maximum load.

As a matter of comparison the average analyses of the Colorado River water at extreme low water, for 3 weeks, January 10, 20, and 26, 1925, are given.

TABLE No. III.—ANALYSIS OF THE COLORADO RIVER AT LOW WATER.

Total soluble salts	1493 parts per million
Calcium (Ca)	148 parts per million
Magnesium (Mg)	39 parts per million
Carbonates (CO_3)	24 parts per million
Bicarbonates (HCO_3)	232 parts per million
Chlorine (Cl)	252 parts per million
Sulphates (SO_4)	508 parts per million
Silt	Trace

At this period of flow it is evident that there is a considerable excess of calcium and magnesium over carbonate. The water has a temporary hardness and a decided permanent hardness, and the river at this period carries very little silt. When 1 gram of dry silt was shaken with this water the silt settled rapidly.

It has been the experience of Mr. Porter J. Preston that the silty material is likely to be carried for a considerable period after the actual flood has passed, and that the stream in its low stages is constantly transporting material down-stream that may have been eroded and brought part of the way down by a former flood and lodged along the channel. The water, the analysis of which is shown in Table No. III, was derived largely from the groundwaters along the course, particularly from the groundwaters on either side of the Grand Canyon, which came into the channel by seepage. Such a water would probably not hold any silt in suspension for a very long period, so it seems as though what little silt the river carried at this low-water period was not eroded by this water but that the silt was eroded and brought partly down-stream by a former flood, and that it was being carried as a bed-load.

In September, 1923, a great rain occurred upon the Painted Desert of northern Arizona and the Little Colorado went into flood stage. The analysis of this flood water as it appeared at Yuma, September 26, is shown in Table No. IV.

TABLE No. IV.—ANALYSIS OF THE COLORADO RIVER WATER DURING SEPTEMBER FLOOD.

Total soluble solids	880 parts per million
Calcium (Ca)	108 parts per million
Magnesium (Mg)	16 parts per million
Carbonates (CO_3)	0 parts per million
Bicarbonates (HCO_3)	192 parts per million
Chlorine (Cl)	98 parts per million
Sulphates (SO_4)	288 parts per million
Silt	22,920 parts per million

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It will be seen that the calcium and magnesium content of the water existed as both temporary and permanent hardness. The percentage of calcium and magnesium is also considerably higher than that during the spring flood, but lower than that at extreme low water. The river at this period carried a very heavy load of silt which settled very slowly. Had this silt been eroded by the water whose analysis is shown in Table No. III, it would have settled very rapidly.

Thus, it seems that, while the quality of the water plays an important part in the transportation of silt, it is sometimes difficult to tell from chemical analyses which of two waters will carry the heavier load, unless we know something of the nature of the silt that has been eroded.

Unquestionably the percentage of calcium in solution is the most important factor in the flocculation of silt, but there are other reactions that take place in the solution that either add to or reduce its effectiveness. These reactions will now be discussed briefly.

It has been shown* recently that, if a solution of sodium carbonate is prepared, and gypsum is added to the solution in increasing amounts, the sodium carbonate will be neutralized gradually, and that calcium carbonate will be thrown out of solution. This reaction, however, does not run to a finish, since the amount of sodium carbonate may be reduced to a concentration of about 25 parts per million, but no lower, and this amount of black alkali will persist in the solution even in the presence of a saturated solution of gypsum, if no carbon dioxide is present.

While the Colorado River, for the greater part of the year, contains a considerable excess of gypsum, at the same time the water will often give a strong, alkaline reaction with phenolphthalein, indicating the presence of hydroxyl ions in solution. This color with phenolphthalein appears at extreme low water, when there is unquestionably a large excess of gypsum in solution. It is true that the silt contains a certain amount of calcium carbonate, and in the absence of carbon dioxide this would give a solution containing hydroxyl ions. The water of the river, however, is in equilibrium with the air, and there is always enough carbon dioxide in the air to prevent the calcium carbonate in solution from showing color with phenolphthalein. The color seems to be due, in part at least, to the hydrolysis of sodium carbonate or sodium zeolite.

The suspended load of silt would not be in its present condition had it not come in contact with some dispersing agent. It might have done this before it was eroded, but it looks as if there is enough sodium carbonate (or sodium hydroxide) in the water, the presence of which is often masked by the excess of gypsum, to hold the silt in suspension,

*Breazeale, J. F. & Burgess, P. S. Technical Bulletin No. 6, Arizona Agricultural Experiment Station.

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and that, except at extreme low water, there is never enough gypsum in solution to overcome the effect of the hydrolyzed sodium salt.

The Colorado River is formed by the union of many streams, and no doubt many of these tributaries carry an excess of calcium sulphate, while others carry an excess of black alkali. When one stream that carries gypsum, unites with another stream that carries black alkali, some of the calcium may even be precipitated as calcium carbonate, and, if the concentration of gypsum is great enough, the precipitation may be fairly complete. Usually, however, the concentration is low and the greater part of both the gypsum and black alkali will be held in solution, and in this case the presence of the black alkali may be masked by the excess of gypsum. The black alkali may then disperse the colloids, or it may hold the colloids in suspension that are already dispersed, and the stream may carry a heavy load of silt in spite of its gypsum content.

Suppose that the colloids in the silt load were dispersed while the soil lay *in situ*, or that they were dispersed by the black alkali of the streams in the headwaters. In either case the zeolites would be combined partly with sodium. If a stream carrying gypsum but no black alkali, emptied into the river, equilibrium would soon be established and a certain part of the zeolites would become calcium salts and would be flocculated and precipitated out. The heavier part of the silt-load would, therefore, be the first to go out, while the lighter fraction would be carried on down the river to the lower basin or even to the Gulf of California. Many streams bring gypsum into the Colorado, but the amount thus brought in is not sufficient to coagulate all of the dispersed colloids, or else they would not appear in the lower river basin. We should expect the sediment that is deposited in the valleys in the headwaters of the Colorado to be more granular and less dispersed than that brought down and spread out in the valleys of the lower basin.

Owing to the difference in the quality of the water of the tributaries, the quality of the water of the Colorado may change many times in its flow from its source to its mouth. This phenomenon of a sudden change in the reaction of rivers is common in the West, and in the groundwaters of river basins. This change in the quality of the water may cause a precipitation of silt at any point along the course of the river, and often it may explain why certain materials are laid down as the valley fill at certain places, and why different materials are laid down at other places.

ABSORPTION OF ALKALI BY COLLOIDS

It is a well-known fact that when an alkali, sodium hydroxide for example, is brought in contact with colloidal or any fine material, a part of the alkali will be absorbed and tenaciously held upon the surface

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of the solid particle. If an alkali is once thus absorbed, it is sometimes exceedingly difficult to remove it by washing.

A large sample of Colorado River silt was collected from the edge of an irrigation canal near Yuma, Arizona, and the silt was repeatedly washed with distilled water and filtered by means of a porous filter until it was practically free from soluble salts, particularly gypsum. It was then dried and ground into fine powder. One gram of the silt was then placed in each of seven tubes, and 100 c.c. of sodium hydroxide solution, of the concentrations shown in Table No. V, were added to each tube. The tubes were stoppered, shaken, and allowed to stand for 24 hours, and then titrated for sodium hydroxide. In Table No. V are given the concentrations of the solutions before and after standing in contact with the silt, and the parts per million of OH that were removed from the solution by the silt.

TABLE No. V.—ABSORPTION OF OH FROM SOLUTIONS OF NaOH BY COLORADO RIVER SILT.

No	OH as NaOH added	OH as NaOH found after 24 hours	OH absorbed by 1 gram of silt
1.	400 p. p. m.	386 p. p. m.	14 p. p. m.
2.	350 p. p. m.	335 p. p. m.	15 p. p. m.
3.	300 p. p. m.	286 p. p. m.	14 p. p. m.
4.	250 p. p. m.	235 p. p. m.	15 p. p. m.
5.	200 p. p. m.	182 p. p. m.	18 p. p. m.

The amount of OH ion absorbed by the silt seems to be about the same in all concentrations used and, unless other factors interfere, this amount is sufficient to disperse colloids. It seems that the Colorado River silt, even if it had been flocculated when first eroded, if it had come in contact with black alkali anywhere along its course, would have taken on sodium ions and would have become dispersed.

EFFECT OF THE HYDROXIDES OF SODIUM, POTASSIUM, AND CALCIUM IN FLOCCULATING COLORADO RIVER SILT

It is well known that black alkali will either flocculate or deflocculate a soil, depending upon the amount of alkali present, the lower concentrations tend to deflocculate, while the higher concentrations tend to flocculate the colloidal material. A soil that is badly impregnated with black alkali may, therefore, be permeable to water until a part of this alkali is removed. It must be remembered that sodium carbonate itself, that is, the alkali that is not hydrolyzed, is probably more or less inert, certainly the salt itself is not a dispersing agent. It requires the presence of water and subsequent hydrolysis, with the formation of sodium hydroxide, before dispersion can take place. Both sodium hydroxide and

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potassium hydroxide possess the property of either dispersing or coagulating colloidal material. In order to obtain a comparison between these alkalies the following experiment was conducted.

One gram of Colorado River silt was placed in each of several tubes, and 50 c.c. each of solutions of sodium hydroxide and potassium hydroxide were added to the tubes. The tubes were corked, shaken, and allowed to stand over-night. The approximate concentration of these two alkalies that was required to flocculate the silt and to cause the solutions to settle clear, is shown in Table No. VI. In order to bring out the comparison more clearly the concentration of alkali is expressed in terms of OH.

TABLE No. VI.—EFFECT OF SODIUM HYDROXIDE AND POTASSIUM HYDROXIDE UPON COLORADO RIVER SILT.

No.	OH as NaOH added	Effect upon silt	OH as KOH added	Effect upon silt
1.	0 p. p. m.	Dispersed	0 p. p. m.	Dispersed
2.	50 p. p. m.	Dispersed	50 p. p. m,	Dispersed
3.	100 p. p. m.	Dispersed	100 p. p. m.	Dispersed
4.	150 p. p. m.	Dispersed	150 p. p. m.	Flocculated
5.	200 p. p. m.	Dispersed	200 p. p. m.	Flocculated
6.	250 p. p. m.	Dispersed	250 p. p. m.	Flocculated
7.	300 p. p. m.	Flocculated	300 p. p. m.	Flocculated
8.	350 p. p. m.	Flocculated	350 p. p. m.	Flocculated
9.	400 p. p. m.	Flocculated	400 p. p. m.	Flocculated

This manner of determining the flocculating point of silt is not presented as a method that is applicable to all conditions, neither is any great degree of accuracy claimed for it. It can only be considered as accurate in a comparison with a control. It can be said, however, that under the conditions of this experiment, the Colorado River silt was flocculated at and above concentrations of about 250 to 300 parts per million of OH as NaOH and that the silt was flocculated at and above concentrations of from 100 to 150 parts per million of OH as KOH. If the basic ions, sodium and potassium, were alone concerned in the dispersion of the colloids, there would be a relation existing between these flocculating points very much like that just quoted, or in proportion to their atomic weights, 23 sodium : 39 potassium.

In the next experiment, the effect of calcium hydroxide and barium hydroxide upon Colorado River silt was determined in the manner just described. Boiled water was used and every care was taken to keep the carbon dioxide out of the solution. The results are given in Table No. VII.

As in the case of the sodium hydroxide solutions, some of the alkali was removed from solution by the silt. In the solutions containing 100 parts per million, 32 parts per million of OH from both the calcium

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hydroxide and barium hydroxide were removed from solution.

When expressed in terms of OH, no difference was noticed in the concentrations of calcium hydroxide and barium hydroxide that were required to flocculate the silt. Above concentrations of 30 or 40 parts per million of OH, both of these alkalies flocculated the silt readily, while below these concentrations the alkalies seem to be practically inert. There was no indication of a greater dispersion than that which existed in the control, in the lower concentrations of alkali. When flocculated with calcium hydroxide or barium hydroxide the silt settled much more rapidly than it did when flocculated with sodium hydroxide or potassium hydroxide.

TABLE No. VII.—THE EFFECT OF CALCIUM HYDROXIDE AND BARIUM HYDROXIDE UPON COLORADO RIVER SILT.

No.	OH as $Ca(OH)_2$ added	Effect upon silt	OH as $Ba(OH)_2$ added	Effect upon silt
1.	0 p. p. m.	Dispersed	0 p. p. m.	Dispersed
2.	5 p. p. m.	Dispersed	5 p. p. m.	Dispersed
3.	10 p. p. m.	Dispersed	10 p. p. m.	Dispersed
4.	20 p. p. m.	Dispersed	20 p. p. m.	Dispersed
5.	30 p. p. m.	Dispersed	30 p. p. m.	Dispersed
6.	40 p. p. m.	Flocculated	40 p. p. m.	Flocculated
7.	50 p. p. m.	Flocculated	50 p. p. m.	Flocculated
8.	60 p. p. m.	Flocculated	60 p. p. m.	Flocculated
9.	70 p. p. m.	Flocculated	70 p. p. m.	Flocculated
10.	80 p. p. m.	Flocculated	80 p. p. m.	Flocculated
11.	90 p. p. m.	Flocculated	90 p. p. m.	Flocculated
12.	100 p. p. m.	Flocculated	100 p. p. m.	Flocculated

The concentration of calcium hydroxide that was required to flocculate the silt was shown in another way. One gram of silt was placed in a large test tube with 100 c.c. of a solution of calcium hydroxide which contained 750 parts per million of OH. The solution was shaken and the silt was flocculated and settled rapidly. One half, or 50 c.c., of the clear solution was drawn off and 50 c.c. of carbon-dioxide-free water were added to the tube. The addition of this water lowered the concentration of the calcium hydroxide to 375 parts per million of OH, and the silt remained flocculated and settled rapidly. This process was continued until the concentration of the OH in the tube was down to about 47 parts per million, when a slight dispersion of the silt set in. Below 47 parts per million of OH the silt remained dispersed.

It looks as though the sodium hydroxide and potassium hydroxide are concerned with both flocculation and deflocculation, while calcium hydroxide and barium hydroxide are concerned with flocculation only. Thirty parts per million of OH is equivalent to over 65 parts per million of calcium hydroxide, so it appears that concentrations of less than

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65 parts per million of calcium hydroxide are practically inert, as far as flocculating clay colloids is concerned. This is a very important fact in the consideration of the silt-carrying capacity of rivers.

EFFECT OF GYPSUM UPON THE FLOCCULATION OF COLORADO RIVER SILT

As the Colorado River silt is readily flocculated by strong solutions of gypsum, an effort was made to determine how strong concentrations of calcium sulphate were required to flocculate the silt. The experiment was carried on as before, and the results are shown in Table No. VIII.

TABLE No. VIII.—EFFECT OF CALCIUM SULPHATE SOLUTIONS UPON COLORADO RIVER SILT.

No.	Parts per million $CaSO_4$ added	Effect upon the silt
Control	0	Dispersed
1.	25 p. p. m.	Dispersed
2.	50 p. p. m.	Dispersed
3.	75 p. p. m.	Dispersed
4.	100 p. p. m.	Slightly dispersed
5.	125 p. p. m.	Flocculated
6.	150 p. p. m.	Flocculated
7.	200 p. p. m.	Flocculated
8.	250 p. p. m.	Flocculated
9.	300 p. p. m.	Flocculated
10.	400 p. p. m.	Flocculated

Under the conditions of this experiment, at concentrations of about 100 parts per million or less, solutions of gypsum are not effective in flocculating Colorado River silt. It requires a concentration of over 100 parts per million to produce decided effects. One hundred parts per million of calcium sulphate equal about 55 parts per million of calcium hydroxide, so there seems to be a molecular relation between the amount of calcium hydroxide and calcium sulphate required to flocculate the Colorado River silt.

EFFECT OF CALCIUM SULPHATE UPON COLORADO RIVER SILT IN THE PRESENCE OF SMALL AMOUNTS OF SODIUM CARBONATE

Another set of calcium sulphate solutions, of the same concentrations shown in Table No. VIII, was prepared, and 30 parts per million of sodium carbonate were added to each of the solutions, and the flocculating effect of these mixtures was determined. Little or no increase was found in the concentration of calcium sulphate that was required to flocculate the silt in the presence of a small amount of black alkali, over that required when no black alkali was added to the solution. This fact

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seems significant. The untreated dry silt, when shaken with carbon-dioxide-free water, gives a color with phenolphthalein, indicating that the solution contains free hydroxl ions. If these ions, or the sodium ions that are dissociated with them, are responsible for the dispersion, the addition of a little more alkali as sodium carbonate would probably have little effect. This phenomenon strongly indicates that the silt as it floats dispersed in the river, carries a small amount of absorbed black alkali and a negative charge, even though an excess of gypsum exists in the solution.

FLOCCULATION OF COLORADO SILT AT FLOOD AND AT LOW WATER

Two conditions in the quality of the Colorado River water were now assumed, and two sets of solutions were made up to represent these conditions. In the first case the water was assumed to have a concentration of calcium about equal to that found at flood time, 30.8 parts per million of calcium or about 105 parts per million of calcium sulphate, and in the second case the water was assumed to have a concentration of calcium about equal to that at extreme low water, 150 parts per million of calcium or about 510 parts per million calcium sulphate. Sodium carbonate was added to portions of each of these solutions in amounts shown in Tables Nos. IX and X, and the effect of these solutions in flocculating the silt was determined, in the manner previously described.

TABLE No. IX.—EFFECT OF SMALL AMOUNTS OF CALCIUM SULPHATE IN THE PRESENCE OF VARYING AMOUNTS OF SODIUM CARBONATE UPON COLORADO RIVER SILT.

No	$CaSO_4$ added	$CaSO_4$ equivalent to Ca	Na_2CO_3 added	Na_2CO_3 equivalent to Ca	Effect upon silt
1.	0 p. p. m.	0 p. p. m.	0 p. p. m.	0 p. p. m.	Dispersed
2.	105 p. p. m.	30.8 p. p. m.	11.0 p. p. m.	4.2 p. p. m.	Dispersed
3.	105 p. p. m.	30.8 p. p. m.	33.3 p. p. m.	12.6 p. p. m.	Dispersed
4.	105 p. p. m.	30.8 p. p. m.	55.5 p. p. m.	21.0 p. p. m.	Dispersed
5.	105 p. p. m.	30.8 p. p. m.	77.7 p. p. m.	29.4 p. p. m.	Dispersed
6.	105 p. p. m.	30.8 p. p. m.	99.9 p. p. m.	37.8 p. p. m.	Dispersed
7.	105 p. p. m.	30.8 p. p. m.	122.1 p. p. m.	46.2 p. p. m.	Dispersed
8.	105 p. p. m.	30.8 p. p. m.	144.0 p. p. m.	54.6 p. p. m.	Dispersed
9.	105 p. p. m.	30.8 p. p. m.	166.0 p. p. m.	63.0 p. p. m.	Dispersed

Each of these solutions gave a color with phenolphthalein, indicating the presence of hydroxyl ions, and in every solution the silt remained dispersed. In solutions Nos. 2, 3, 4, and 5 the amount of calcium sulphate was more than equivalent to the amounts of sodium carbonate added, but the excess of calcium sulphate apparently had no effect upon the silt. Some of these solutions are representative of the quality of

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the Colorado River at flood time, when it is carrying a heavy load of silt.

In Table No. X, is shown the effect of a large amount of calcium sulphate in the presence of varying amounts of sodium carbonate.

Some of the solutions are representative of the quality of the Colorado River at low water, when it is usually carrying its lightest load of silt. Although each of the solutions gave a color with phenolphthalein, in all of the solutions except the last three and the control, the

TABLE No. X.—EFFECT OF LARGE AMOUNTS OF CALCIUM SULPHATE IN THE PRESENCE OF VARYING AMOUNTS OF SODIUM CARBONATE, UPON COLORADO RIVER SILT.

No.	$CaSO_4$ added	$CaSO_4$ equivalent to Ca	Na_2CO_3 added	Na_2CO_3 equivalent to Ca	Effect upon silt
1.	0 p. p. m.	0 p. p. m.	0 p. p. m.	0 p. p. m.	Dispersed
2.	525 p. p. m.	154 p. p. m.	13 p. p. m.	5 p. p. m.	Flocculated
3.	525 p. p. m.	154 p. p. m.	27 p. p. m.	10 p. p. m.	Flocculated
4.	525 p. p. m.	154 p. p. m.	54 p. p. m.	21 p. p. m.	Flocculated
5.	525 p. p. m.	154 p. p. m.	109 p. p. m.	42 p. p. m.	Flocculated
6.	525 p. p. m.	154 p. p. m.	222 p. p. m.	84 p. p. m.	Flocculated
7.	525 p. p. m.	154 p. p. m.	333 p. p. m.	126 p. p. m.	Slightly dispersed
8.	525 p. p. m.	154 p. p. m.	444 p. p. m.	168 p. p. m.	Slightly dispersed
9.	525 p. p. m.	154 p. p. m.	555 p. p. m.	210 p. p. m.	Dispersed

silt was flocculated. It will be noted that the dispersion of the silt began with solution No. 7, although in that and the next solution there was still an excess of calcium sulphate over the sodium carbonate. In the last number only was sodium carbonate added in excess of the gypsum. The solutions in numbers 7 and 8 suggest the actual condition of affairs as often occurs in the Colorado River itself, that is, the river often contains a large excess of calcium sulphate, yet at the same time it contains a small amount of sodium carbonate.

EFFECT OF NEUTRAL SODIUM SALTS UPON COLORADO RIVER SILT

There are other salts in the Colorado River water that also have an effect upon its silt-carrying capacity; these are sodium sulphate and sodium chloride. In practice, we know that these salts in appreciable amounts have a flocculating effect upon colloids, from the fact that a soil high in sodium sulphate or sodium chloride will usually take water readily, and will remain permeable until most of these salts are leached out. The amounts of sodium chloride or sodium sulphate in solution in the Colorado River water varies with the flood. The chlorine content may vary from 42 to 250 parts per million while the SO_4 content may

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run as low as 80 parts per million at flood times and as high as 600 parts per million at low water.

Many experiments were made to determine the amounts of sodium chloride and sodium sulphate that had a flocculating effect upon the Colorado River silt, but the results were not conclusive and they are not included. Usually a concentration of about 650 parts per million of sodium sulphate, and a slightly less amount of sodium chloride, is sufficient to flocculate the silt, but often a greater amount is required. There is usually no definite change from dispersion to flocculation, as the concentration of the sodium salt is increased.

The peculiar effect of the sodium salt upon the silt may be explained by the fact that the silt contains a certain amount of calcium carbonate and that when sodium sulphate or sodium chloride is brought in contact with this calcium carbonate, a certain amount of sodium carbonate is formed in the reaction. In the concentration of salt in the Colorado River water, the amount of sodium carbonate thus formed would be small, yet very small amounts of sodium carbonate have a decided effect in dispersing colloids, and it is quite possible that the flocculating effect of sodium sulphate and sodium chloride is in part counteracted by the presence of small amounts of black alkali in the solution. It can be stated definitely, however, that sodium sulphate and sodium chloride seldom occur in Colorado River water in amounts sufficiently high to have a decidedly flocculating effect upon the silt.

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SUMMARY

1. The silt, as it floats in the Colorado River, seems to be dispersed, that is, the colloidal particles seem to be carrying negative charges.

2. In many cases, the silt-carrying capacity of a stream may depend upon the size of the particles in suspension, rather than upon the velocity of the current.

3. The colloids in the Colorado River silt were probably dispersed when they existed as soils in the upper water shed, before they were eroded.

4. The silt, as it is deposited in the lower basin, contains appreciable amounts of replaceable sodium, indicating the presence of dispersed colloids.

5. The quality of the Colorado River water varies with the flood. At low water it has a high salt-content, and contains an excess of gypsum, but during the spring flood, its concentration of soluble salts is low, and it may even carry a slight excess of black alkali.

6. The hydroxides of sodium and potassium when added to the water in low concentrations, disperse the Colorado silt but they flocculate the silt when added in high concentrations.

7. The hydroxides of calcium and barium seem to be inert in very low concentrations, but they flocculate the silt at and above concentrations of about 40 parts per million of OH.

8. Sodium and potassium hydroxides seem to be associated with both flocculation and dispersion, while calcium hydroxide and barium hydroxide seem to be associated with flocculation only.

9. Calcium sulphate flocculates the silt at and above concentrations of about 100 parts per million, but in lower concentrations calcium sulphate seems to be relatively inert.

10. Although the Colorado River water usually contains an excess of calcium sulphate, it does not always carry this salt in amounts sufficiently high to flocculate the silt.

11. Sodium sulphate and sodium chloride have a flocculating effect upon the silt, but these salts seldom occur in amounts sufficiently high to make them effective.

12. The quality of the water, as well as the velocity of the current, should be taken into consideration in many of the engineering problems that involve the silt-carrying capacity of streams.

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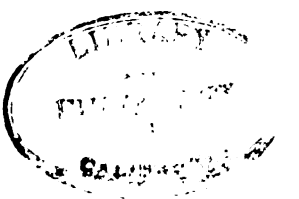
METHODS FOR DETERMINING THE REPLACEABLE BASES OF SOILS, EITHER IN THE PRESENCE OR ABSENCE OF ALKALI SALTS

By P. S. Burgess and J. F. Breazeale



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METHODS FOR DETERMINING THE REPLACEABLE BASES OF SOILS, EITHER IN THE PRESENCE OR ABSENCE OF ALKALI SALTS

By P. S. Burgess and J. F. Breazeale

INTRODUCTION

The subject of base replacement in soils has received extensive attention over a long period of years by some of the world's most distinguished agricultural chemists. Its importance in soil economy is unquestionably great, for by such replacements are the bases used by plants largely rendered available. By the same reactions, fertilizer salts are retained against wasteful leaching and loss, and Gedroiz and Kelley each has shown recently that the formation of black alkali in arid and semi-arid soils may also be accounted for, in part at least, by such base exchanges, with subsequent hydrolysis. Just as black alkali may be formed in soils by base exchanges (usually Na for Ca), so must it be reclaimed in similar manner, but by the reverse reaction (Ca for Na). The reclamation of alkali lands will ever be a most important factor in the agriculture of the Southwest, hence any information which may help—either in its understanding or practice—should receive careful consideration.

It has long been known that one base may replace another in the soil hydrated aluminum silicates or "zeolites." Calcium for example may replace sodium, and sodium in turn may replace calcium, depending upon the concentration of the ions in solution. If, therefore, a normal, arable soil that contains a considerable amount of replaceable calcium and no replaceable sodium, is percolated with a solution of sodium chloride of sufficient concentration, the sodium will replace the calcium and become "fixed" in the soil, while the calcium will go into solution and come through with the percolate as calcium chloride. Such replacements as the one just described will bring about a very decided physical change in soil texture. The normal soil doubtless was originally flocculated and permeable to water, while the same soil, after it has been leached with a sodium chloride solution, and subsequently with pure water until free from salt will be dispersed and impermeable. If the dispersed soil is now percolated with a solution of calcium chloride, the calcium will replace the absorbed sodium, and the soil will become again flocculated and freely permeable to water.

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THE CALCIUM : SODIUM RATIO

Irrigation agriculture and the reclamation of alkali lands, depend to a great extent upon soil permeability, or the ability of a soil to "take water," and this is determined largely by its degree of dispersion. In a study of the replaceable bases of the soil, it has been the hope of many investigators to obtain a mathematical expression for permeability in terms of replaceable sodium or replaceable calcium, or in terms of a ratio between these two bases. The value of such an expression is evident. It would enable the farmer, from an analysis, to predict the approximate speed of water penetration and he could thus be governed in his irrigation practices. Efforts to obtain such mathematical expressions, however, thus far have been disappointing.

In working with dispersed, calcareous soils, such as occur in the vicinity of Tucson, it has been our experience that the ratio of replaceable sodium to replaceable calcium has little or no meaning when applied to permeability, that is, one cannot expect a soil that runs 10 replaceable sodium to 1 of replaceable calcium, to be more impermeable than a soil that runs 1 replaceable sodium to 10 replaceable calcium. In fact it seems that the lower the percentage of sodium, often the more highly dispersed the soil, regardless of the calcium content.

The ratio of replaceable sodium to replaceable calcium depends upon a variety of conditions, one of which is the moisture content of the soil. If a moist soil that contains sodium zeolite, calcium zeolite, and calcium carbonate, is dried out, as for example between irrigations, the percentage of replaceable sodium is gradually increased while that of replaceable calcium is proportionately decreased. A perfectly dry, calcareous soil is likely to be hard and highly dispersed. Upon the addition of water the replaceable sodium is gradually decreased and the replaceable calcium is proportionately increased. If the addition of water is carried on indefinitely, or if the soil is thoroughly leached, practically all of the sodium zeolite will be converted into calcium zeolite. In other words, upon dilution, the sodium zeolite is hydrolyzed and the sodium is replaced by the calcium that formerly was in combination as calcium carbonate. Calcium seems to possess the ability to change from the carbonate into the zeolite, and back again into the carbonate as moisture conditions change. It is thus a reversible reaction.

In practice, if a dispersed, calcareous soil is irrigated, and leached with fairly pure water, the sodium zeolite will gradually hydrolyze and be removed in the drainage. At the same time, although the calcium is gradually entering into combination with the zeolite, the soil becomes more and more impermeable to water. Finally, when but a trace of sodium

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remains, the soil often becomes so dispersed that it is almost impossible to get water through it. This conditon has put an end to many attempts at reclamation.

Water penetration is absolutely essential in the reclamation of alkali land, and the final state of dispersion does not take place until nearly all of the alkali has been removed. The soil that is thus almost free from alkali would probably be good for agricultural purposes, if it were not so dispersed. The difficulty at this stage seems to be a purely mechanical one, and the application of gypsum, or other soluble calcium salt, will accomplish much good. Occasionally, however, the application of gypsum is not economical, so if a practical method of obviating the difficulty caused by this final state of dispersion could be found, it would solve an important problem of alkali reclamation.

In some sections of Arizona the farmers are successfully reclaiming dispersed or "slick" spots in their fields by raising borders around these spots, bringing the soil to a perfect level, and keeping a good head of water on the spots for a long period of time. The downward movement of the water may eventually become very slow. This takes place when the percentage of sodium zeolite in the soil is probably near the minimum. With a little perseverance, if the head of water is maintained, the soil often begins to improve slowly in permeability. The soil may thus be reclaimed without the addition of gypsum or other flocculating agents. We have demonstrated this to be a fact in the laboratory and in the field. The plan seems to work best when the plots are leached, then dried out, leached again, and so on.

It is a relatively easy matter, under laboratory conditions, to obviate this final dispersion of the soil which has just been described. One of the soil types on the University of Arizona Farm contains a little black alkali, is highly dispersed, and only slightly permeable to water. If a sample of this soil is placed in a percolating tube and distilled water added at the top of the column, the water will percolate slowly for probably twenty-four hours, then percolation will practically cease.

A 500-gram sample of this soil was placed in a jar and 2 liters of distilled water added to it. The mixture was shaken, allowed to stand overnight, and the solution decanted and filtered under pressure through a porous, porcelain filter. The filtrate was saved, while the soil that adhered to the filter candle was washed back into the jar with the rest of the soil, and 2 liters more of water added. This was shaken and filtered as before. This operation was continued until 11 large bottles, holding 2,500 c. c. each, had been progressively filled with the percolate. Five hundred grams of soil had, therefore, been leached with 27,500 c. c. of

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water. The solutions were now analyzed and the analyses are given in Table I.

TABLE I.—GRAMS OF SOLUTES REMOVED BY PERCOLATE FROM EACH 100 GRAMS OF SOIL.

No.	Total solids	Calcium	Magnesium	CO_3	HCO_3	Cl	SO_4
1.	0.371	Trace*	Trace	0.030	0.072	0.070	0.113
2.	0.122	Trace*	0	0.036	0.036	0.010	Trace
3.	0.082	Trace*	0	0.024	0.036	0	0
4.	0.069	Trace*	0	0.018	0.030	0	0
5.	0.047	Trace*	0	0.018	0.006	0	0
6.	0.029	Trace*	0	Trace	0.030	0	0
7.	0.028	Trace*	0	Trace	0.030	0	0
8.	0.026	Trace*	0	Trace	0.030	0	0
9.	0.018	Trace*	0	Trace	0.024	0	0
10.	0.015	Trace*	0	Trace	0.021	0	0
11.	0.025	Trace*	0	Trace	0.024	0	0

*Due to slight solution of $CaCO_3$.

The percolates showed little or no calcium or magnesium. The carbonates decreased gradually as the leaching proceeded. The soil was calcareous, so the final traces of alkalinity were probably due to the solubility of calcium carbonate.

After leaching, the soil was dried, placed in a tube and percolated with pure water. It took water freely and showed no signs of being dispersed. The physical properties of the soil had been changed, it was no longer gummy, but seemed to be in good, mechanical condition.

The replaceable sodium and replaceable calcium were determined in the leached soil by the method that will be described and these results are shown in Table II, in comparison with the results obtained from a sample of untreated soil.

TABLE II.—REPLACEABLE Ca AND Na IN 100 GRAMS OF SOIL.

	Replaceable calcium	Replaceable sodium
Untreated soil	0.0370 gm.	0.1771 gm.
Leached soil	0.1320 gm.	0

It will thus be seen that the sodium carbonate and zeolite had been hydrolyzed and removed completely from the soil during the leaching process, and that the sodium had been replaced by the calcium that originally existed as calcium carbonate, even though $CaCO_3$ is soluble to the extent of only 6 or 8 parts per million of solution.

The phenomenon above described has been demonstrated in other ways. The gradual replacement of the sodium by calcium during the leaching process has been followed. At the point where percolation almost

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stops, the amount of replaceable sodium in the soil is usually very low. A trace of replaceable sodium may, therefore, cause a decided dispersion in a heavy soil.

It thus may be safe to assume that a high percentage of replaceable sodium in a soil cannot be correlated with a high degree of dispersion and impermeability, and that little or no idea of the degree of dispersion of a soil can be gained from the study of the Ca: Na ratio. As long as there is an appreciable amount of replaceable sodium present (which gives up OH ions to the soil solution) the soil is almost sure to be dispersed, regardless of the amount of replaceable calcium present.

NEED FOR IMPROVED METHODS

The object of this bulletin is to advance methods whereby replaceable bases may be determined quantitatively and with a minimum expenditure of time and effort in soils ranging in reaction from extreme acidity to high alkalinity, and where alkali salts may or may not be present. So far as the writers have been able to find, no satisfactory methods exist, although much work has been done along this line. Adsorptions, solutions, and side-reactions have crept in, and tended to vitiate many results published heretofore. The bases present in slightly acid and neutral soils are comparatively easy to replace quantitatively, but soils carrying $CaCO_3$ and $MgCO_3$ in considerable quantities, as well as soils high in organic matter and in alkali salts, have presented difficulties which so far have been largely insurmountable.

The displacing solutions most commonly employed heretofore have been those of NH_4Cl, KCl, and NaCl, but, as it is often desirable to determine replaced K and Na, the latter two salts are not always applicable. We thus have NH_4Cl left as the salt at present almost universally used for this purpose. It is unsatisfactory in three important respects. First, where sufficiently large samples of soil are extracted to give proper amounts of Ca, Mg, Na, and K for accurate gravimetric or volumetric determination, and where tenth-normal (or stronger) solutions of NH_4Cl are employed, there remains upon evaporation an enormous amount of NH_4Cl which must be gotten rid of before these determinations can be made. This is often accomplished by volatilization, and, as is well known, where the amounts of NH_4Cl are large, (many grams) and the amounts of Ca, Mg, Na, and K small (often but a few milligrams) the possibilities of error due to mechanical loss are great. Furthermore, such a procedure is time-consuming and requires constant attention. Repeated evaporation with HNO_3, as used in some laboratories for this purpose, is also wasteful of time and disagreeable. The second, and, to us in the arid Southwest, a very important reason for condemning NH_4Cl is that $CaCO_3$ is

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appreciably soluble in its solutions (280 p. p. m. in tenth-normal NH_4Cl). The soils of this section are almost without exception calcareous, varying from 1 to over 50 percent $CaCO_3$, hence any solution which appreciably dissolves this salt is of questionable value where replaceable Ca is to be determined. Magnesium carbonate is also soluble in solutions of NH_4Cl, but to a lesser degree.* The third reason for condemning the use of NH_4Cl as a replacing agent is that it dissolves and removes from the soil large amounts of organic matter (especially from alkaline soils) which, as a soil colloid, may have a bearing on the replacement reaction.

The attention of the writers was first called to the possibility of using solutions of $BaCl_2$ as agents for the quantitative determination of replaceable bases in soils, by C. S. Scofield. It was found, however, that the use of $BaCl_2$ presented serious difficulty in that the several replaced bases could not be quantitatively separated from the excess of Ba by the ordinary methods. The total replacing power of Ba, as compared with mono and trivalent ions had previously been studied by Gedroiz and others, but, so far as the writers know, none had proposed the use of $BaCl_2$ in a method for determining the *amounts* of the several bases replaced. We are thus laying no claim to priority in the use of barium chloride as a replacing agent. We are, however, advancing the method which follows as a means whereby the calcium, magnesium, sodium, and potassium may be quantitatively separated and determined in the barium chloride percolate, thus rendering barium chloride a replacing agent of decided value from both the qualitative and quantitative standpoints. The carbonates of calcium and magnesium are but slightly soluble in tenth-normal solutions of $BaCl_2$, as results soon to be presented will show; it does not dissolve appreciable amounts of soil organic matter, and it is very active as a replacing agent, less prolonged treatment being required than with the salts of the monovalent bases in solutions of equivalent strengths.

THE SOLUBILITIES OF $CaCO_3$ AND $MgCO_3$ IN TENTH-NORMAL NH_4Cl, TENTH-NORMAL $BaCl_2$, AND DISTILLED WATER

When an excess of pure $CaCO_3$ or $MgCO_3$ is shaken with carbon-dioxide-free water until equilibrium is reached, a definite amount of the salt is dissolved, depending upon the temperature. This is a solution phenomenon, pure and simple. When, however, these substances are shaken with solutions of salts, besides true solution, a certain reaction-product results, depending upon the masses of the reacting compounds and their

*Gedroiz states that magnesium carbonate is more soluble in solutions of NH_4Cl than is calcium carbonate. Our work, using finely ground magnesite, is not in agreement with this statement.

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solubilities. For instance, if we shake $CaCO_3$ with a $BaCl_2$ solution we have the following reaction slowly taking place:

$$CaCO_3 + BaCl_2 \rightleftarrows BaCO_3 + CaCl_2 \qquad (1)$$

Thus, depending upon the masses and solubilities involved, more or less $CaCl_2$ is formed which is a soluble salt, and which is the *result of this reaction* rather than a simple solution phenomenon. The same is true where we use NH_4Cl:

$$CaCO_3 + 2NH_4Cl \rightleftarrows (NH_4)_2CO_3 + CaCl_2 \qquad (2)$$

Now, as both compounds on the right side of equation (2) are readily soluble this reaction will proceed fairly rapidly from left to right until little solid $CaCO_3$ remains; but, as $BaCO_3$ is but slightly more soluble than $CaCO_3$, equilibrium is soon reached in equation (1). It will thus readily be seen that much more calcium will be present in solution where a tenth-normal solution of NH_4Cl is used than where a $BaCl_2$ solution of like normality is employed.

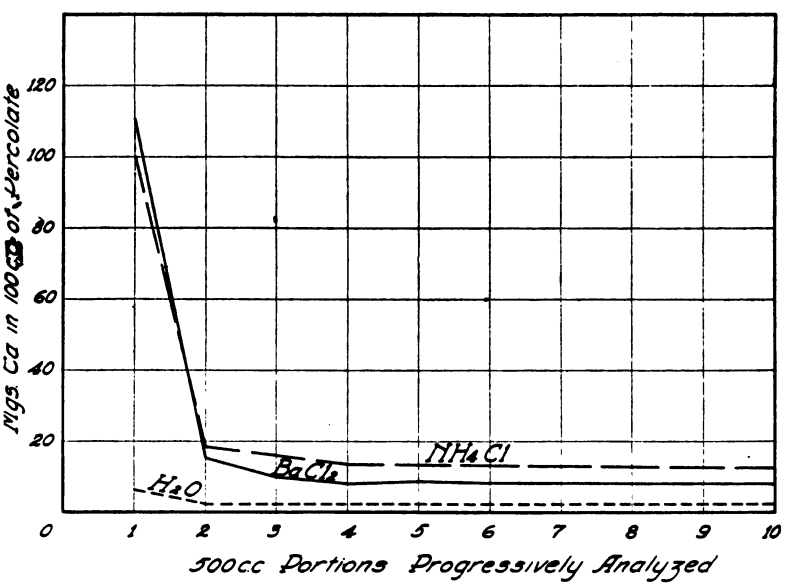

Fig. 1.—Yuma fine sand.

Our first attempts at determining the amounts of $CaCO_3$ and $MgCO_3$ which were dissolved by tenth-normal solutions of NH_4Cl and $BaCl_2$ were made as follows: One-half gram of Kahlbaum's C. P. $CaCO_3$ (or

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$MgCO_3$), which had been washed several times by decantation with carbon-dioxide-free distilled water and subsequently dried, was placed in a hard glass bottle and shaken in a machine for 1 day with 250 c. c. of the salt solution to be tested. At the end of this time it was allowed to stand 1 day (until perfectly clear) when a proper aliquot (10 to 25 c. c.) was withdrawn for analysis. The original solution was then shaken for another day and analyzed again. This was continued several times, and in all cases, except where pure water was used, there was a progressive increase in solubility with each successive period of shaking. This was especially marked in the case of $CaCO_3$ in $BaCl_2$ solution and $MgCO_3$ in NH_4Cl solution.

It was soon realized that data thus secured could not be applied to our method, which was one of percolation rather than shaking. Three glass percolating tubes were, therefore, filled with Yuma fine sand* and

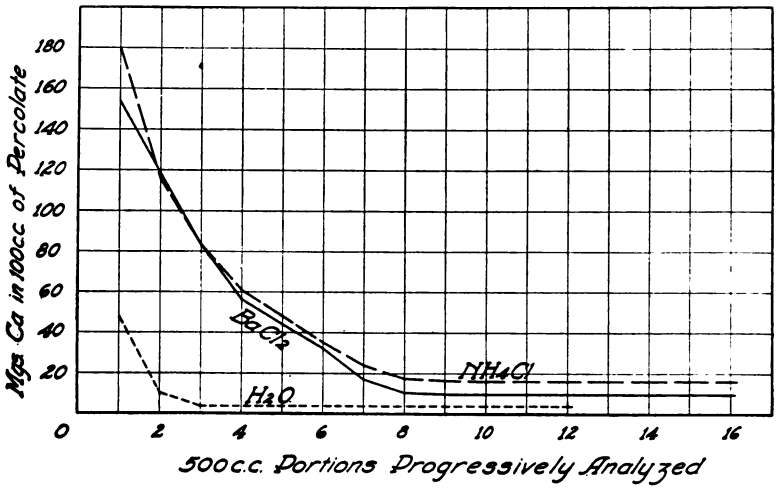

Fig. 2.—Yuma silty clay.

three others with Yuma silty clay.* One tube of each soil was constantly leached with water, one with tenth-normal NH_4Cl, and one with tenth-normal $BaCl_2$. As soon as 500 c. c. of percolate had come through, it was removed and analyzed for soluble calcium in each case. This was continued until ten 500 c. c. portions of each of the three solutions had been analyzed from the sandy soil and sixteen each from the silt.† The

*These soils were purposely chosen because they are both calcareous (the sand carried 3.0 percent $CaCO_3$ and the clay 6.2 percent), and they represent physically two extreme cases, a very light sand and a very heavy, silty clay.

†Only eight 500 c.c. portions of the pure-water percolates from the silt soil were analyzed as here percolation was very slow.

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data thus secured were plotted and appear in figures 1 and 2. As neither of these soils contained appreciable amounts of $MgCO_3$, and as this compound is seldom present in soils unaccompanied by $CaCO_3$, it was decided to set up another similar percolation experiment, using fine, washed, quartz sand impregnated with $MgCO_3$, to obtain similar solubility data for this salt. As it seemed desirable to use a naturally occurring product rather than precipitated $MgCO_3$, a sample of magnesite was secured from the University of Arizona College of Mines and Engineering, having the following composition: MgO 46.26 percent, CaO 1.74 percent, Fe_2O_3 1.27 percent, CO_2 50.48 percent, H_2O nil, insoluble nil, total 99.75 percent. As will be seen, this material analyzed over 96 percent $MgCO_3$. It was finely ground in a ball mill and thoroughly incorporated with the quartz sand at the rate of 2 percent by weight. Three portions of 125 gm. each were placed in small glass percolators and treated with water, tenth-normal NH_4Cl and tenth-normal $BaCl_2$ as above, each 100 c. c. of percolate being progressively analyzed for soluble magnesium. The rate of flow was regulated (by rubber tubing and clamps at the lower apertures of the percolating tubes) to permit 100 c. c. to pass through in approximately two hours. The results secured have been plotted and appear in figure 3.

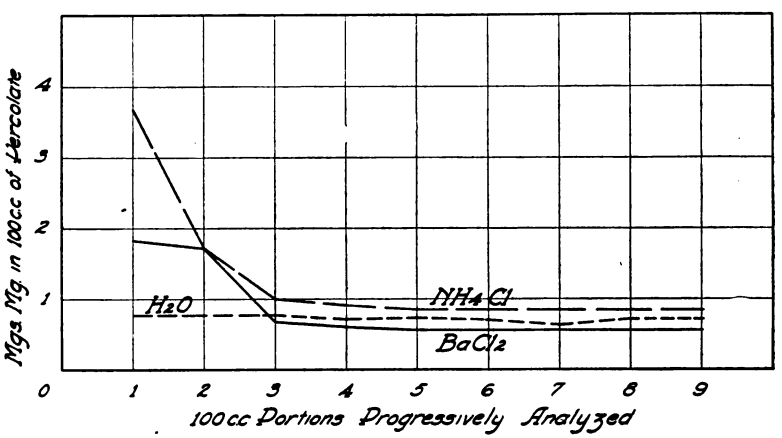

Fig 3.—Finely ground magnesite in quartz sand.

In none of the percolation tests was carbon-dioxide-free water used. Ordinary distilled water was employed throughout, and conditions maintained as nearly like those where replaceable bases were to be determined by our methods, as possible. It was our aim here to determine the errors due to solubilities and side-reactions incurred by the presence of the earthy

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carbonates. The Yuma soils carried traces of gypsum which accounts for the relatively larger amounts of water-soluble calcium shown in the first two extractions (see Figs. 1 and 2). Thereafter the curves for distilled water ran practically parallel with the base line, showing that the resulting small amounts of calcium were being progressively dissolved from the solid $CaCO_3$ present in the soils. This amounted to approximately 10 p. p. m. of solution (doubtless present in part as calcium bicarbonate) in the case of the sandy soil, and 25 p. p. m. where the clay soil was employed. After the curves for NH_4Cl and $BaCl_2$ had flattened out, i. e., when all of the readily soluble and replaceable calcium had been removed, we found, in the case of both soils, that the tenth-normal $BaCl_2$ extracts much less calcium from the residual $CaCO_3$ than does the tenth-normal NH_4Cl. In the case of the sandy soil (Fig. 1), where percolation is fairly rapid, the NH_4Cl removes in solution approximately 110 p. p. m. of calcium, while the $BaCl_2$ removes 70 p. p. m. In the case of the heavy soil (Fig. 2) an average of 135 p. p. m. of calcium is removed by the NH_4Cl, while less than 60 p. p. m. is leached out by the $BaCl_2$. Expressed in percentages of soil employed, where, let us say, 2 liters of percolate are secured and

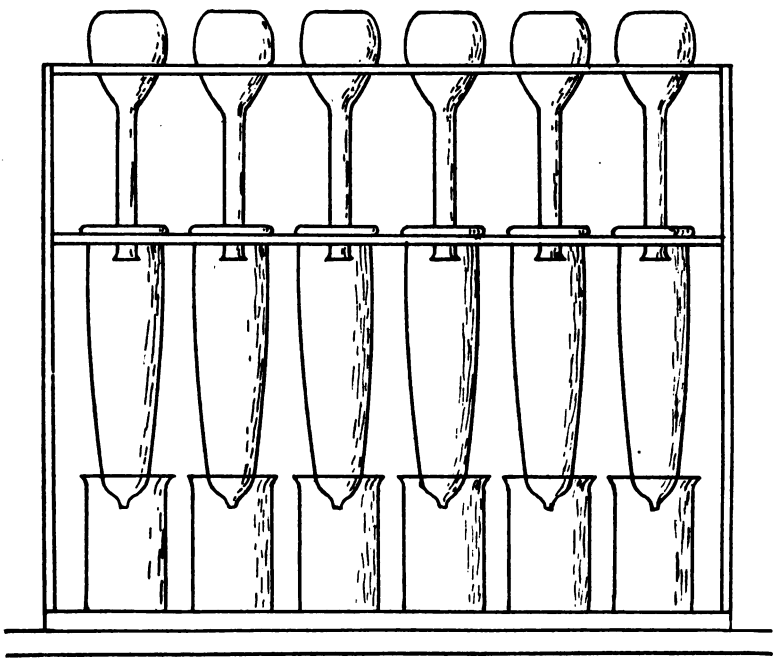

Fig. 4.—Wooden rack carrying percolators and flasks used in leaching soils.

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analyzed, the errors, especially with the $BaCl_2$ solution, are relatively small. For example, 800 grams of soil were used in each of the above tests, and 2 liters of percolate secured, which would carry *in solution* approximately 120 mgs. of calcium, which would represent a positive error of 0.015 percent. If great accuracy is desired, this percentage may be subtracted from the figure found for replaceable calcium in calcareous soils where 2 liters of percolate are secured.

Figure 3 shows the amounts of magnesium dissolved by the two salt solutions and by distilled water from the magnesite-impregnated sand. After the first two 100 c. c. portions had passed through the percolators, the amounts of magnesium dissolved were thereafter fairly constant for each solution used, and in no case were they of sufficient magnitude to cause trouble. It will be noticed that the amounts removed in tenth-normal $BaCl_2$ are often less than are those dissolved in distilled water, while the opposite is always true for tenth-normal NH_4Cl.

METHOD FOR DETERMINING REPLACEABLE BASES IN CALCAREOUS SOILS FREE FROM BLACK ALKALI

The method finally adopted for the determination of replaceable bases in calcareous soils free from black alkali (white alkali does not interfere unless large amounts of gypsum are present) is as follows:

Five hundred grams (or 100 grams if high in clay) of air-dry soil are placed in a glass percolating tube (see Fig. 4) and leached with tenth-normal $BaCl_2$ solution until free from replaceable Ca (700 c. c. to 2,000 c. c. depending upon soil texture). The percolate is then made up to a definite volume (1 or 2 liters) with distilled water, and if at all turbid (which is not usual) filtered through a porcelain pressure filter. Two hundred c. c. are placed in a 250 c. c. graduated flask, 4 or 5 drops of con. acetic acid, and 20 c. c. of sodium chromate solution (175 gm. Na_2CrO_4 : 10 H_2O per liter) are added in the cold to precipitate the barium. The whole is made up to 250 c. c., thoroughly agitated, and allowed to stand overnight to clear. Careful examination has shown no absorption of either Ca or Mg by the $BaCrO_4$ precipitate. Two methods of procedure are here possible. The Ca and Mg may be determined by the soap-titration methods, or by the standard methods, after separating them from the chromate solution. Both are often used in this laboratory as checks.

SOAP-TITRATION METHODS FOR Ca AND Mg

These methods which are modifications of the old Clarke method are extremely accurate where small amounts of Ca and Mg (7 mgs. or less) are present in the aliquot taken, and where Ca is in excess of Mg, or where

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either is present alone. These conditions, incidentally, usually prevail in the salt solutions carrying replaced Ca and Mg from soils.

For the Ca determination take an aliquot of the clear, yellow, supernatant liquid carrying not over 6 or 7 mgs. Ca (5 to 25 c. c.), place it in a 250 c. c. bottle, make up to approximately 50 c. c. with distilled water, add 2 or 3 drops of concentrated NH_4OH and 5 c. c. of the alkaline tartrate solution.* Titrate, with shaking, against the standard soap solution* until a permanent froth remains after 2 minutes' standing. This reading, minus 0.3 c. c., multiplied by 0.00075 gives grams of Ca in the aliquot taken.

For the Mg determination take another aliquot carrying not over 6 or 7 mgs. of combined Ca and Mg, place in a 250 c. c. bottle, make up to approximately 50 c. c. with distilled water, add 2-3 drops of con. NH_4OH and 5 c. c. of the alkaline-ammonium-chloride solution.† Titrate as above to a permanent froth, being careful not to be misled by the "false foam" which often occurs at the Ca "end point." Subtract 0.3 c. c. from the final reading, which is the sum of the Ca and Mg present in the aliquot taken. Subtract the Ca reading already obtained from this total and multiply the remainder by 0.00039, this gives grams of Mg in the aliquot taken.

STANDARD METHODS

Pipette off an aliquot of the clear, yellow, supernatant liquid (100 or 150 c. c.). Make alkaline with NH_4OH and add, with stirring, sufficient 2 percent amonium-acid-phosphate solution, in the cold, to precipitate completely the Ca and Mg as phosphates,‡ as in the ordinary precipitation of magnesium. Let stand overnight, filter, wash with 2 percent NH_4OH, dissolve the precipitate in a small amount of hot, dil. HCl, make up to a volume of about 100 c. c. with distilled water and bring to boiling point. Add *just enough* NH_4OH to make slightly alkaline and throw out the phosphates, then with stirring, add 10 c. c. of a 5 percent solution of oxalic acid and boil. The solution now should be distinctly acid, while the Ca will be precipitated completely as the oxalate. Filter and determine the Ca by titrating with a standard solution of $KMnO_4$.

*The reagents are made up as follows:

Standard Soap Solution: A little over 13 gm. of C. P. sodium oleate (Merck's) are dissolved in 1 liter of 50 percent ethyl alcohol and standardized against a Ca solution of known strength (a saturated solution of C. P. gypsum contains 0.210 percent $CaSO_4$ and is usually used in this laboratory) so that each c.c. equals 0.00075 gm. of calcium. *Alkaline Tartrate Solution*: Dissolve 12 gm. of potassium hydroxide and 200 gm. of sodium-potassium-tartrate in 1 liter water.

†*Alkaline-Ammonium-Chloride Solution*: Dissolve 20 gm. ammonium chloride in 1 liter water carrying 70 c.c. of concentrated C. P. ammonium hydroxide.

‡See, "The Determination of Calcium in the Presence of Phosphates," by Breazeale in Jour. A. O. A. C., V. 4, p. 124.

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Evaporate the filtrate to a bulk of about 50 c. c., cool, add 2 or 3 c. c. of the amonium-acid-phosphate solution and precipitate the Mg as $MgNH_4PO_4$ by making alkaline with NH_4OH in the usual way, igniting, and finally weighing as $Mg_2P_2O_7$.

Sodium and potassium are determined in the original $BaCl_2$ percolate as follows: An aliquot (usually 100 c. c.) is placed in a porcelain evaporating dish, slightly acidified with HCl and 5 c. c. (or more) of a 14-percent solution of $(NH_4)_2 SO_4$ added. Evaporate to dryness on the water bath, dry in the oven, and drive off slight excess of ammonium salts in the electric muffle at low heat, finally heating to *dull* redness. Take up in 2 percent HCl, digest on the water bath for an hour or more, filter, and determine Na and K by Hilgard's Method or by the Official Methods of the A. O. A. C. The $BaSO_4$, *after heating*, has little or no tendency to absorb sodium and potassium. This, however, is not true in the cases of calcium and magnesium. If replaceable K only is desired, the procedure is greatly simplified. After digesting the residue in dil. HCl, filter into a porcelain evaporating dish, add the proper amount of platinic chloride solution and gravimetrically determine K in the usual way.*

Where the soils carry white alkali (sulphates and chlorides of sodium) the soil in the percolator must first be leached free from these salts with pure water before being subjected to the $BaCl_2$ treatment,† or, where percolation with water is slow as in the case of heavy soils, a separate analysis may be made for water-soluble bases and these subsequently subtracted from those found in the $BaCl_2$ percolate.

In the case of acid soils (unsaturated with respect to bases), the amounts of replaceable H-ion may be determined in the $BaCl_2$ percolate by means of titrations as recently recommended by Gedroiz,‡ and modified by Joffe and McLean.§

TESTS OF THE PROPOSED METHOD WHERE BLACK ALKALI IS ABSENT

On several occasions during the past year in which this method has developed in our laboratory, standard stock solutions of the chlorides of

*See, Official Methods of Analysis of the A. O. A. C. (2nd Edition) p. 14, Sec. 45a.

†Where gypsum (which is but slightly soluble and slowly leached out of soils) is present in considerable quantities, the method here proposed cannot be used, for, after the more readily soluble sodium salts have been removed, the calcium, slowly coming into solution as leaching is continued, will replace zeolitic sodium. Low results will thus be obtained for replaceable sodium (and potassium) and too high results for replaceable calcium. Gypsum, however, is seldom present in such large quantities.

‡"A Method of Determining the H-Ion Absorbed in the Soil, etc.," by K. K. Gedroiz, In Zhur. Opit. Agr. (Jour. Expt. Agr.) Vol. 22. pp. 1-28.

§"Colloidal Behavior of Soils and Soil Fertility: II The Soil Complex Capable of Base Exchange and Soil Acidity," by J. S. Joffe and H. C. McLean, Soil Science, Vol. 21, No. 3, pp. 181-195, (1926).

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Ba, Ca, Mg, Na, and K have been prepared, from which both "known" and "unknown" solutions have been made up and subjected to analysis by one or the other of the authors. It is not our intention to give all of the data secured. It was thought, however, that a certain amount of it should be included to substantiate our claims as to the accuracy of the separations.

Fairly concentrated solutions of the chlorides of Ca, Mg, Na, and K were prepared so that 5, 10, or 15 c.c. only were required to furnish all of each base added, while tenth-normal $BaCl_2$ was used in all cases to bring the solutions up to a volume of 250 or 500 c.c., as the case might be. A majority of the work has been done intentionally with the elements Ca and Mg for the reasons that these elements are more subject to adsorptions during separations, and furthermore, the accurate determination of the amounts of these elements *in replaceable forms* is of considerable importance in the study of alkali soils carrying large amounts of their carbonates. Table III presents the very first of these data secured.

TABLE III.—AMOUNTS OF Ca AND Mg ADDED AND RECOVERED FROM MIXED SOLUTIONS OF THEIR CHLORIDES IN THE PRESENCE OF AN EXCESS OF $BaCl_2$.

No.	Mgs. added		Mgs. recovered by soap-titration methods		Mgs. recovered by standard methods	
	Ca	Mg	Ca	Mg	Ca	Mg
1	20	12	20.0	11.0	20.4	10.7
2	40	12	40.2	10.4	40.4	12.5
3	20	24	22.4	24.4	20.8	19.0
4	10	6	11.6	5.7	10.6	7.0
5	30	6	30.0	4.1	30.7	5.3
6	10	36	.....	31.0	11.0	32.0

In all but two or three cases these figures are in very fair agreement, and showed at the outset that the method had promise of possibly somewhat greater exactitude after more care and time had been expended upon it.

The accuracy of the potassium determination was next tested with the results appearing in Table IV.

The agreement in Table IV appears to be all that one could desire. No adsorption of K by the $BaSO_4$ precipitate is indicated. Calcium and magnesium also were present here in small quantities to find whether or no they interfered with the potassium determination. Calcium and magnesium were not determined.

The sodium determination in the presence of tenth-normal $BaCl_2$ by the method above outlined was tried, with the results set forth in Table V. The solutions were made up with pure NaCl and $BaCl_2$. No other salts were present.

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TABLE IV.—AMOUNTS OF K ADDED AND RECOVERED FROM SOLUTIONS OF KCl IN TENTH-NORMAL $BaCl_2$ IN THE PRESENCE OF SMALL AMOUNTS OF $CaCl_2$ AND $MgCl_2$.

No.	Mgs. K added as the chloride	Amounts recovered	
		Wts. K_2PtCl_6	Mgs. K
1	4	0.0310 gm.	4.90
2	8	0.0500	8.04
3	12	0.0770	12.30
4	16	0.1025	16.30
5	20	0.1170	18.90
6	24	0.1560	25.00
7	28	0.1695	27.40
8	40	0.2435	39.20

These results show little or no adsorption of Na by the ignited $BaSO_4$ precipitate.

TABLE V.—AMOUNTS OF Na ADDED AND RECOVERED FROM SOLUTIONS OF NaCl IN TENTH-NORMAL $BaCl_2$.

No.	Mgs. Na added as the chloride	Amounts recovered	
		Wts. Na_2SO_4	Mgs. Na
1	20	0.0644 gm.	20.8
2	30	0.0921	29.8
3	40	0.1180	38.5
4	50	0.1460	47.3

Four solutions of 250 c.c. each were made up to contain the following amounts of Ca, Mg, K, and Na as chlorides, dissolved in tenth-normal $BaCl_2$:

TABLE VI.—COMPOSITION OF TEST SOLUTIONS.

No.	Mgs. Ca	Mgs. Mg	Mgs. K	Mgs. Na
1	100	60	100	25
2	150	30	80	50
3	40	90	60	75
4	60	120	40	100

From time to time, as opportunity permitted, these solutions, or solutions of the same concentrations, were analyzed, different aliquots often being taken. The results secured appear in Table VII.

These analyses were made later on, after considerable experience had been gained with the method. In all cases very good agreement is shown between the weights of the several elements contained in the aliquots taken, and those recovered upon analysis. No adsorption of Ca and Mg by the $BaCrO_4$ precipitates, or of Na and K by the ignited $BaSO_4$ precipitates is indicated.

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TABLE VII.—MILLIGRAMS OF Ca, Mg, K, AND Na ADDED AND RECOVERED FROM SOLUTIONS OF THEIR CHLORIDES, IN THE PRESENCE OF TENTH-NORMAL $BaCl_2$.

No.	Calcium						Magnesium						Potassium		Sodium	
	Aliquot contained	Recovered*	Aliquot contained	Recovered	Aliquot contained	Recovered	Aliquot contained	Recovered	Aliquot contained	Recovered	Aliquot contained	Recovered*	Aliquot contained	Recovered	Aliquot contained	Recovered
1	4	3.8	20	20.4	15	14.6	24	22.6	9	9.0	2.8	2.4	40	38.2	10	10.1
2	6	6.0	30	30.4	22.5	22.0	12	11.5	4.5	4.8	1.4	1.4	32	29.1	20	20.5
3	1.6	1.8	8	8.4	6	6.4	36	34.8	13.5	13.0	4.2	4.5	24	22.6	30	29.9
4	2.4	2.3	12	12.0	9	9.0	48	____	18	17.4	5.6	5.4	16	16.5	40	39.3

*Soap-titration method used.

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Four solutions were prepared by one of the writers and analyzed as "unknowns" by the other. They contained Ca and Mg only. The results secured are recorded in Table VIII.

TABLE VIII.—AMOUNTS OF Ca AND Mg RECOVERED FROM "UNKNOWN" SOLUTIONS OF THEIR CHLORIDES IN THE PRESENCE OF AN EXCESS OF $BaCl_2$.

No.	Mgs. added		Mgs. recovered by soap-titration methods		Mgs. recovered by standard methods	
	Ca	Mg	Ca	Mg	Ca	Mg
1	20	12	20.0	7.8	20.0	12.0
2	50	30	52.5	31.0	50.0	30.6
3	70	42	70.0	44.0	70.0	40.2
4	120	60	122.5	56.5	118.0	60.4

Where the standard methods (titration of Ca with $KMnO_4$ and gravimetric determination of Mg as $Mg_2P_2O_7$) were employed, the methods here advocated are as accurate as needful. While the soap-titration methods are subject to slightly greater variations where large amounts of Ca and Mg are present (due to multiplication of error from aliquot taken), the extreme rapidity of operation is here a factor to be considered where large numbers of such determinations are to be made.

METHOD FOR DETERMINING REPLACEABLE BASES IN CALCAREOUS SOILS WHERE BLACK ALKALI IS PRESENT

In the West, many soils contain black alkali, or sodium carbonate, and this salt is always associated with dispersion if the soil carries much clay and silt. Dispersed soils aways contain a certain amount of sodium that is combined as zeolite (basic-hydrated-aluminum silicate), and such soils are nearly always calcareous. We thus have sodium existing as the carbonate, the bicarbonate, and the zeolite, in the presence of an excess of calcium carbonate. In reclamation work and in our percolation studies we are concerned with sodium zeolite fully as much as with sodium carbonate. Sodium carbonate is but slightly hydrolyzed and does not completely retard percolation, as it is readily soluble and may be slowly leached from soils. On the other hand, sodium zeolite is only slightly soluble, and cannot be washed out readily from soils, due to almost complete hydrolysis of the dissolved portion.

In the methods for the determination of replaceable bases in alkali soils that have so far been proposed no attention has been given, and no attempt has been made to separate the sodium that may be combined in the hydrated silicate molecule from that which may be combined with

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the CO_3 radical. The sodium is either reported as replaceable sodium, or as sodium carbonate (black alkali). In ordinary alkali-soil analyses where an excess of water is used, the sodium, whether it is derived originally from the carbonate or the zeolite, is reported as sodium carbonate. If a soil is digested with an equal weight of water, all of the sodium carbonate and a very small part of the sodium zeolite will go into solution, but if the ratio of water to soil is increased to say 5 to 1 or 10 to 1, as is often the case, the sodium zeolite is hydrolyzed further, or possibly completely, and we titrate it as hydrolyzed sodium carbonate in the resulting solution. Ordinary analyses are, therefore, only arbitrary, unless sufficient amounts of water are used to bring about complete hydrolysis of the sodium zeolite, and in this way bring all of the sodium into solution. Even then the sodium determination would represent the total soluble sodium and there would be no distinction made between that originally existing as carbonate, and the zeolite. A method which will distinguish between the sodium that is combined with the CO_3 ion and that existing as zeolite should be, therefore, of considerable value.

THE TWO-TUBE PERCOLATION METHOD

Two samples of dry soil of 500 gm. each (or 100 gm. if high in clay) are placed in two percolating tubes and treated as follows:

Tube No. 1. Percolated with n/10 $BaCl_2$ until soil bases are all replaced (shown by qualitative test in percolate for Ca). Solution A.

Tube No. 2. Percolated with n/10 $CaCl_2$ until Mg, Na, and K are all replaced—until no more Ca is being fixed by the soil. Determined by titrating the percolate and the original solution for Ca. Solution B.

Tube No. 2 is now leached with pure water until all the $CaCl_2$ solution is removed. This leaching water is discarded. The soil column is now leached with n/10 $BaCl_2$ until all the Ca has been replaced by the Ba. Solution C.

Solutions A, B, and C are now titrated for combined Ca and Mg by the soap-solution method, as these two bases act very similarly in soils, or they may be determined gravimetrically. In this discussion for the present they will be considered together, the term Ca being assumed to mean both Ca and Mg.*

The Ca content of Solution A is the total replaceable Ca in the soil.

The Ca content of Solution B is determined, and the difference in the Ca content of this percolate and that of the original n/10 $CaCl_2$ used, represents the Ca equivalent of both the sodium carbonate and sodium zeolite originally present in the soil. The Ca of the n/10 $CaCl_2$

*Incidentally, replaceable Mg is usually *very low* in calcareous soils carrying black alkali.

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solution has liberated the Na in the sodium zeolite and is now present as calcium zeolite in the soil. The Ca in the $CaCl_2$ solution has also combined with the CO_3 radical formerly present as Na_2CO_3, and been precipitated in the soil as $CaCO_3$, which is insoluble. Thus, the total amount of Ca fixed by the soil is equivalent to the Na originally existing both as the carbonate and as zeolite. A little Na_2CO_3 may be brought into the percolate during the first stages of the leaching process and should be poured back through the soil, in order to be sure that all of the Na_2CO_3 has reacted, with the formation of the insoluble $CaCO_3$. The $NaHCO_3$ which may be present in the soil in small amounts, causes no trouble whatever, as the soluble calcium bicarbonate (if formed at all) comes through with the the excess $CaCl_2$ present, and it is the difference between the amounts of Ca in the original solution and in the percolate, which is fixed, and which is of interest.

Solution C contains both the Ca which was originally present in the soil as calcium zeolite, and the Ca from the calcium zeolite formed from the sodium zeolite by the preceding percolation with $CaCl_2$ solution. This total amount of replaceable Ca was replaced by the Ba, and came through into the percolate as $CaCl_2$. *It should be remembered here that the Ca that reacted with the Na_2CO_3 was precipitated in the soil as $CaCO_3$, and does not enter into this reaction.* Calcareous soils already contain an excess of $CaCO_3$, and this precipitation adds but a very small amount in addition. Thus, the Ca in Solution C represents the replaceable Ca of the soil together with the Ca equivalent of the Na derived from the sodium zeolite originally present in the soil.

In calculating the results of the analyses of the three percolates for Ca, an outline of the analysis of the University Farm Soil may be helpful. The results are expressed as percent of dry soil.

ANALYSIS OF SOLUTIONS

Sol.	Ca	Ca equivalent of:
A	0.0350	Calcium zeolite present in soil
B	0.1790	Sodium zeolite plus Na_2CO_3 present in soil
C	0.1650	Calcium zeolite plus sodium zeolite present in soil

Now C minus A equals sodium zeolite.
B minus sodium zeolite equals Na_2CO_3.

Or:
0.1650—CaZ plus NaZ
0.0350—CaZ
0.1300—NaZ
} All in Ca equivalents.

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0.1790—NaZ plus Na_2CO_3
0.1300—NaZ
0.0490—Na_2CO_3
} All in Ca equivalents.

We thus have, in terms of Ca, for the soil in question:

Replaceable Ca	0.0350 percent
Ca equivalent to replaceable Na	0.1300 percent
Ca equivalent to Na_2CO_3	0.0490 percent

As Ca is bivalent, and Na monovalent, 20 of Ca is equivalent to 23 of Na, thus calculating Na from Ca equivalent, we have:

Replaceable Ca	0.0350 percent
Replaceable Na	0.1495 percent
Na as Na_2CO_3	0.0563 percent

In the case of soils carrying water-soluble Ca, the amount of this base must be determined by leaching another similar column with distilled water and subtracting the results obtained from the data secured by the replacing solutions noted above.

It will be noticed that this method involves the determination of Ca only, in so far as the replaceable Na is concerned. This is a decided advantage, as all analysts know, for the Na determination is tedious and subject to many chances for error.

If we are desirous of determining the exact amounts of replaceable Ca, Mg, Na, and K, as well as black alkali (Na_2CO_3), it may be done as follows:

Another aliquot of Solution A is taken and the separation of Ca and Mg here made by means of sodium chromate, as in the method above described.

K also may be readily separated and determined in another aliquot of Solution A, as in the first method. Its Na equivalent is calculated and subtracted from the percentage of replaceable Na found.

CONCLUSIONS

The quantitative determination of replaceable bases (Ca, Mg, Na, and K) in soils is often desirable, as such exchangeable bases play an important part in plant nutrition and in black alkali formation in many arid western soils.

Methods are here advanced for making such quantitative determin-

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ations in acid, neutral, or calcareous soils. The methods are also modified to minimize, or entirely do away with complications arising from the presence of soluble alkali salts which are often present in considerable quantities in the soils of the West.

Tenth-normal barium chloride is employed as the replacing agent, the Ba being later removed from solution as $BaCrO_4$ where Ca and Mg are to be determined, or $BaSO_4$ (ignited) where Na and K are sought. Solutions of $BaCl_2$ have often been used as base replacing agents, but, so far as the authors are aware, no quantitative method using such solutions, has been heretofore advocated. This has doubtless been due to difficulties encountered in quantitatively separating Ca and Mg from the excess of the Ba present in the solutions where the ordinary methods of precipitation are followed.

In the case of black alkali soils (soils carrying Na_2CO_3), a method for the determination of replaceable bases is proposed, which involves analyses for calcium only, thus doing away with the tedious sodium determination.

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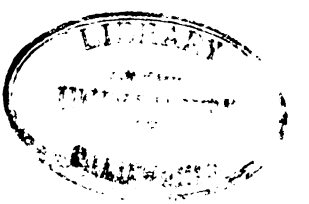
THE AVAILABILITY OF PHOSPHATES IN CALCAREOUS OR ALKALINE SOILS

By J. F. Breazeale and P. S. Burgess



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FOREWORD

Although a large amount of field experimental work has been done upon the subject of commercial fertilizers, the fundamental reasons that underlie the practice are little understood. Some soils respond to a certain fertilizer, while other soils, apparently of the same chemical and physical composition, do not. If the human race is to survive, the fertility of the soil must be maintained, and the maintenance of soil fertility probably always will involve the use of commercial fertilizers.

When brought under cultivation, the soils of the arid West and Southwest generally are rich in the mineral elements of plant food and are wonderfully productive, but it is only a matter of time when this native fertility will be reduced, so as to make the application of fertilizers necessary. In many places crop yields are now on the decline, due, in part, to the loss of fertility of the soil. Of the mineral elements in these soils phosphorus seems to be the most deficient, and there are indications that this element is the limiting factor in crop production in many soils.

Western soils are known to differ from many soils in the humid regions, in that they often respond to applications of acid or superphosphates but not to insoluble phosphates, such as floats or bone meal. This phenomenon has been made the subject of this bulletin.

In order to conduct experimental work with fertilizers intelligently, it is necessary to have a knowledge of the reactions in the soil under different conditions. This bulletin deals with the chemical reactions that take place when both soluble and insoluble phosphates are added to calcareous or alkaline soils; it explains the role of carbon dioxide in the soil solution, interprets observed phenomena, and offers a sensible working hypothesis for future work.

J. J. THORNBER,
Director.

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THE AVAILABILITY OF PHOSPHATES IN CALCAREOUS OR ALKALINE SOILS

By J. F. Breazeale and P. S. Burgess

INTRODUCTION

It has been shown repeatedly that, in certain localities, insoluble phosphate* such as finely ground phosphate rock—commonly known as floats—is rendered available, if first mixed with manure or other organic matter and then applied to the soil. Furthermore, it is well known that soils high in organic matter, such as the fertile soils of the Middle West, are more likely to respond to applications of insoluble phosphate than are soils that are low in organic matter. Upon much of the red clay soil in the Piedmont section of the South, where such marked effects with soluble or acid phosphates are obtained in growing cotton, little or no effects are obtained from applications of floats. These cotton-producing soils are usually very low in organic matter.

In the Southwest, especially in the Lower Colorado Valley, and in other places in Arizona, the same phenomenon is noticed under a set of conditions different from those existing in the South. Although these soils may contain an abundance of organic matter, no effects are obtained from applications of insoluble phosphates. However, the effect of soluble phosphate upon a variety of crops is very pronounced.

Nearly all of the arid soils of the West, when brought under cultivation, are rich in total phosphorus, and the soils of the Lower Colorado Valley and Arizona are no exceptions to this general rule. Yet, while these soils are known to contain a relatively high percentage of total phosphorus, or of the phosphates that are soluble in strong acids, many of them respond markedly to applications of soluble phosphate. The increase in yields of crops that have been fertilized with soluble phosphate has been noticed repeatedly upon our experimental plots, and upon private farms in different parts of the State.

Acid phosphate is a comparatively cheap fertilizer, and there is no reason why it should not play an important part in the maintenance of soil fertility in the Southwest. An accurate knowledge of the conditions under which a benefit from its application may or may not be expected,

*In deference to custom, the term "insoluble phosphate" will be used in this bulletin to designate the slightly soluble forms, such as finely ground apatite, South Carolina or Florida rock, or bone meal. It is recognized that all of these so-called insoluble phosphates have a low solubility. It should be noted also that, while these phosphates usually are referred to as tri-calcium, $Ca_3(PO_4)_2$, it is the opinion of many investigators that they are either a solid solution of di-calcium phosphate in calcium oxide, $Ca_2(HPO_4)_2+CaO$, or tri-calcium phosphate with an excess of calcium hydroxide, $3Ca_2(PO_4)_2.Ca(OH)_2$.

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is, therefore, exceedingly important. These facts seemed to justify research work upon this subject.

The reaction of plants toward applications of phosphates under western conditions, has interested a great many people. Hilgard recognized the importance of fertilizing arid soils with soluble phosphates, and he also observed the lack of positive results from applications of insoluble phosphate. On page 393 of "Soils," he says:

> "The forecast that for most California soils, fertilization with phosphates is of exceptional importance, has already been abundantly confirmed by cultural experience. Few definite data are, as yet, available from other arid states, where fertilization is thus far sporadic and unsystematic. But it is predictable that in view of the presence of this excess of lime carbonate in arid soils, and the unfavorable effect of this compound on the rapid solubility of tri-calcic phosphate demonstrated by Schloesing, Jr., by Bottcher and Kellner, and Nagaoka, fertilization with readily available phosphate fertilizers will be found necessary among the first, all over the arid region, especially in view of the scarcity of humus in arid soils."

Practically all of the arid, upland soils of the West are calcareous and it is evident that Hilgard attributed the results of applications of insoluble phosphates to this fact. This, no doubt, has an effect, in a manner that will be explained later, but there are other reasons that are probably more potent than is the mere presence of an excess of calcium carbonate in the soil.

EXPERIMENTS WITH SOILS FROM THE LOWER COLORADO VALLEY

Four large soil samples representing soils that respond to applications of soluble phosphates, were collected from the Experiment Station plots of the United States Department of Agriculture, Bard, California. These soils were collected in the autumn of 1925, and had received the treatments described in Table I in the spring of that year. The soil samples were dried and shipped to Tucson, where the experiments were conducted. The soils were calcareous, and showed a trace of black alkali.

TABLE I.—TREATMENT OF SOILS.

1.	Control plot (D 23).
2.	Plot that had received an application of bone meal at the rate of 600 lbs. per acre (D 22).
3.	Plot that had received an application of 16 percent acid phosphate at the rate of 900 lbs. per acre (D 23).
4.	Plot that had received an application of 44 percent superphosphate at the rate of 545 lbs. per acre (D 26).

The soils were used as collected from the field, without additional applications of phosphate.

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PREPARATION OF THE SOIL EXTRACTS

Two thousand grams of each soil were weighed out, placed in a large bottle and 4,000 c.c. of distilled water added. This mixture was shaken in a machine for about half an hour, allowed to stand overnight, and the solutions or extracts were filtered through porous filter cores under pressure. The same core was used for soil No. 1 throughout the experiment, and the core was not washed between filtrations. Another core was used for soil No. 2, and so on. These cores had been in use in the laboratory for several months, and gave up no phosphorus to the extract and absorbed practically nothing from it.

One hundred seedlings of oats or barley were grown in about 2,000 c.c. of each of these extracts, and the extracts were changed every day. In order to make this change, the plants were allowed to grow in one portion of the extract for one day while the soil was being shaken and digested with another part of the same extract. When the extract was filtered off from the soil on the following day, the extract that the plants had been growing in during the previous day was poured back upon the soil. None of the extracts were thrown away, but in this way were used over and over again, and allowed to become saturated by standing in contact with the soil every other day.

PREPARATION OF CULTURE PLANTS

Under the conditions that existed during these experiments, it was found best first to malt the oat and barley seeds by soaking them in water for a few hours and then roll them in wet towels until the plumules and radicals appeared. They were then sprinkled upon perforated aluminum discs that floated in pans of tap water. A photograph of one of these discs, showing the glass floats, is given in figure 1.

When the plumules had reached a length of about one centimeter, they were counted out and, one at a time, removed from the seed-bed discs, and placed upon other discs that were floating on the pans containing the soil extracts. Under ordinary conditions, the little seedlings, when thus transplanted, will send their roots down through the perforations of the discs and grow readily. A disc of seedlings that was removed from one of the culture pans, after 3 weeks' growth, is shown in figure 2.

After the seedlings had grown in the culture solutions for the required period, from 25 to 50 representative plants were removed from each culture pan, dried, weighed, and analyzed for phosphorus. The increase in the phosphorus content of the plants over that contained in the control, or in the plants that grew in distilled water, represents the phosphorus that had been absorbed from the solution.

By using the plant in this way as an indicator, a distinction may be made between the plant food that is soluble and the plant food that is available.

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Certain plant foods may be in the form of an aqueous solution and yet not be available to plants.*

PROBABLE ERROR

While there is always a variation in seedlings, even with the most skilled technique, every care was taken to reduce this error to a minimum. Seedlings, even when grown in distilled water, will vary in ash content, if results of analyses are expressed in terms of a hundred plants. This variation is due largely to the difference in the size and composition of the original seeds. Even if it is assumed that the original seeds were of uniform size and composition, a variation must be expected in the seedlings.

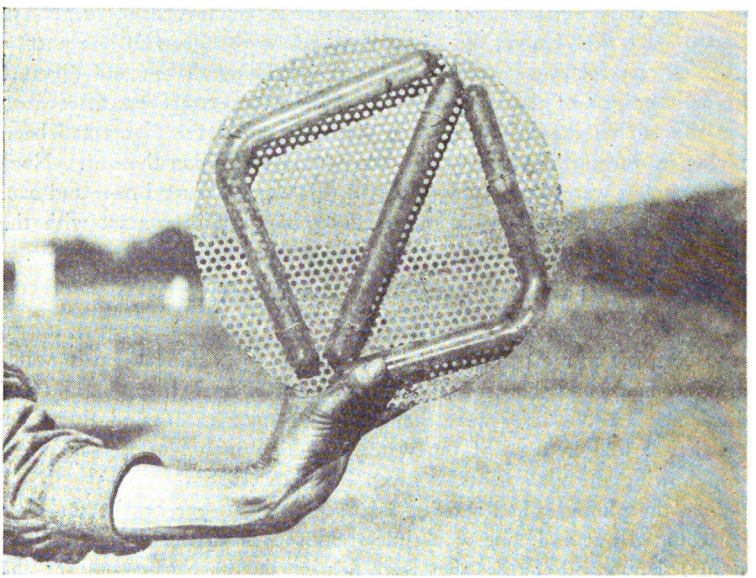

Fig. 1.—Aluminum culture disc, showing glass floats.

That is, a set of a hundred barley seedlings, if grown for a few weeks in distilled water, will not necessarily analyze exactly the same as a set that is grown from the same kind of seed at another time. The variation in such cases is usually small, but in working with a few parts per million, it must be considered. Barley, oat, and wheat seedlings, if soaked in water preparatory to germination, will exude a certain amount of salts, particularly potassium and phosphate ions, into the solution. This phos-

*Breazeale, J. F., Jour. Agr. Res. Vol. XX, No. 8. Jan. 15, 1921. Concentration of Potassium in Orthoclase Solutions, not a Measure of its Availability to Wheat Seedlings.

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phate or other plant food will be absorbed by the seedlings as soon as they start growing. One hundred grams of barley were soaked overnight in about 125 c.c. of water, and the seeds exuded .0148 gram of phosphorus into the solution, and more phosphorus might have been exuded if the measurements had been continued throughout the germination process. It is almost impossible to carry on seedling work under uniform conditions, as there is no practical way of determining how much salt has been exuded, or how much has been reabsorbed by the plants. This error will depend largely upon the amount of water that the seeds have come in contact with, upon the temperature of the water, and upon other factors.

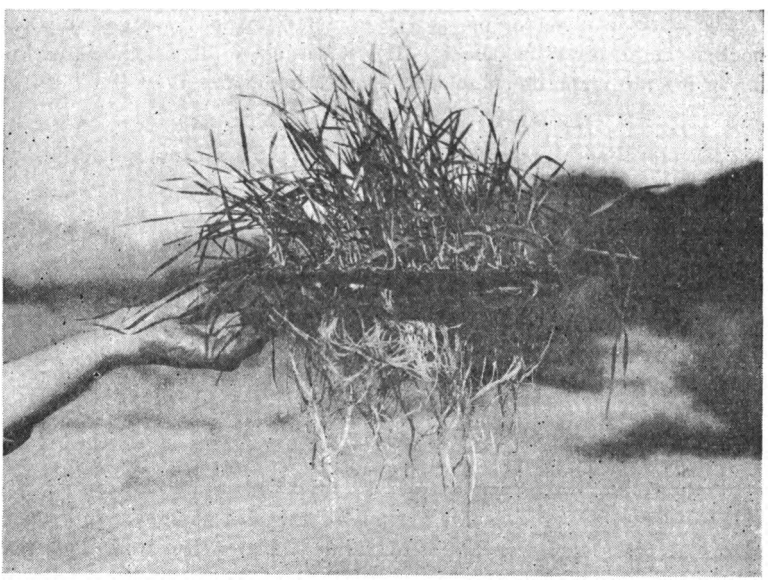

Fig. 2.—A disc of seedlings, three weeks old.

In these experiments the seeds were treated as the occasion seemed to justify. The seeds were always malted in order to get the best germination. Occasionally they were soaked in a large amount of water, but usually they were only moistened and wrapped in wet towels before they began to sprout prior to placing them upon the aluminum discs that were used as seedbeds. The seedlings were carefully counted as they were withdrawn from the seedbed, and particular attention was given that no unsprouted seed should be carried along with the sprouted seedlings, as the plant food from unsprouted seeds diffuses into the solution and is absorbed by the growing seedlings.

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In running the controls of these experiments, it seemed advisable to have a control culture pan for each set, and to base all calculations upon this control. These control plants were selected from the same seedbeds as were the rest of the set, they had the same treatment, they looked alike, they had the same average-size plumules, and approximately the same root development. This seemed to be about as fair a control as it was possible to get, and in the determination of very small amounts of plant food in the seedlings, this matter of fair control is an exceedingly important one. In the experiments that follow, different varieties of seeds were used, so the control of one set must not be compared with the control of another.

The error involved in the analytical determinations was probably too small to be of any consequence. It was possible to obtain checks within 0.3 or 0.4 milligram of phosphorus upon each sample.

EXPERIMENTS WITH SOIL EXTRACTS

Barley seedlings were grown for 19 days in the soil extracts described in Table II, and then analyzed for phosphorus.

TABLE II.—ABSORPTION OF PHOSPHORUS FROM EXTRACTS BY BARLEY SEEDLINGS.

	Grams in 100 plants	
	Dry wt.	Phosphorus
1. Distilled water control	2 560	01387
2. Extract of soil from the control plot	2 472	.01425
3. Extract of soil from bone-meal plot	2 840	.01409
4. Extract of soil from 16% acid-phosphate plot	2 744	.01566
5. Extract of soil from 44% superphosphate plot	2 742	01630

The plants that grew in the extracts of the acid-phosphate and superphosphate plots, Nos. 4 and 5, were distinctly better than were those that grew in the extracts of the bone-meal and control plots. This effect is not shown in the dry weights of the crops. However, this is often the case; the dry weights of seedlings are not a safe criterion in culture work, when working with the effect of phosphorus. The phosphorus content of the plants that were grown in the extracts was different, however. The plants that were grown in the bone-meal extract showed little or no increase in phosphorus over the control soil extract or the distilled water control. The most marked increase in phosphorus was in the plants that had been grown in the superphosphate-soil extract. As the plants in the control soil extract contained very little more phosphorus than did those that were grown in distilled water, it is reasonable to assume that practically no phosphorus went into solution from the control soil. If any had gone into solution, the little seedlings unquestionably would have absorbed

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it, and it would have been shown in the analysis of the ash. These results are distinct and cannot be explained upon the basis of the possible error of the experiment.

Oat seedlings also were grown in these soil extracts under conditions similar to those under which the barley seedlings were grown. In Table III are shown the analyses of oat plants that were under observation for 15 days.

TABLE III.—ABSORPTION OF PHOSPHORUS FROM EXTRACTS BY OAT SEEDLINGS.

	Grams in 100 plants	
	Dry wt.	Phosphorus
1. Distilled water control	3.040	.01371
2. Extract of soil from control plot	3.592	.01355
3. Extract of soil from bone-meal plot	3.160	.01296
4. Extract of soil from 16% acid-phosphate plot	3.176	.01528
5. Extract of soil from 44% superphosphate plot	3.800	.01555

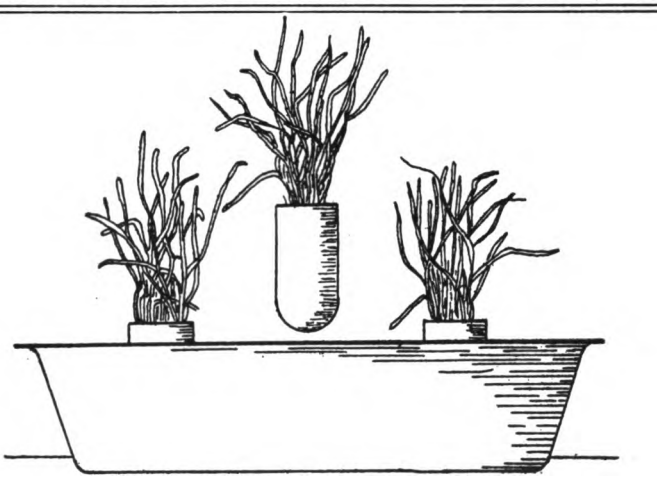

Fig. 3.—A drawing illustrating culture scheme, using filter paper thimbles.

It will be seen that the results with oat seedlings were similar to those with barley, that is, no absorption of phosphorus was obtained from the control soil extract as shown by a comparison with the distilled water control. The plants in the bone-meal soil extract were even slightly deficient in phosphorus. There was, apparently, no soluble phosphorus either in the control soil or in the bone-meal soil extract. The plants that grew in the extracts of the superphosphate and acid-phosphate soils were distinctly higher in phosphorus than were the others. Evidently these soils were transmitting their good or poor properties to their extracts.

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EXPERIMENTS WITH FILTER PAPER THIMBLES

This method of study, that involved the use of filter paper extraction thimbles, was probably never before adapted to soil culture work, but it appears to have promising possibilities. A drawing of the culture scheme is shown in figure 3.

In this method, 5,000 grams of soil were weighed out and placed in a porcelain pan. This amount of soil was sufficient to fill the pan almost to the top. Six filter paper thimbles such as are ordinarily used in the determination of crude fiber, were then imbedded in the soil around the outer edge of the pan. The thimbles were made of thick filter paper and were 33 mm. in diameter and 80 mm. in length, and when pushed into the soil in the pan, they stood about 10 mm. above the soil. Twenty-five seedlings were placed in each of these thimbles and held in place with cotton batting. A little well was then made in the center of each pan of soil, and distilled water was poured into these wells and allowed to soak out through the soil and into the filter paper thimbles. The plant roots grew in the soil extract inside the thimbles.

In the first trials the roots grew through the filter paper and out into the soil, but this trouble was obviated by taking the seedlings lightly between the forefinger and thumb and turning them about half a revolution each day. With this treatment, the roots grew in a bunch and remained inside the thimbles. It would have been an easy matter to have added nitrogen, potash, and other plant foods to the solution inside the thimbles, and to have carried the plants to maturity, but this was not done. The soil in the pans was kept saturated during the experiment.

As is well known, it is exceedingly difficult to grow young plants in a saturated soil without drainage, as they usually turn yellow and die within a few days. With the thimble method, the plants grow in the soil extract and behave like ordinary water cultures.

The thimble method eliminates certain serious objections which have been raised to many soil fertility investigations. In this method the soil extract filters through the thimbles and comes in contact with the roots, clear and free from suspended matter. The whole plant may then be used for analysis. This is not possible in culture studies when direct contact of the plant root and the soil is made, as it is practically impossible to get all of the roots out of the soil and have them free from adhering material. Plants that have the same top development may have a different root system. The plant food is distributed between the top and the root, so it is evident that the anaylsis of the top of a plant having a small root, may show more plant foot than the analysis of the top of a plant having a large root.

With the thimble method we also eliminate the possibility of the plant

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exuding acids or solvents, that may dissolve insoluble soil constituents and thereby bring plant foods into solution that otherwise would not be available.

Several times during the experiment the solutions were drawn out from the inside of the thimbles, and conductivity measurements made upon them. It is interesting to note that the ohms resistence of these solutions was practically the same as was that of the extracts that were made by shaking the soils with twice their weight of water and filtering the extracts through porous filter cores, as was done in the experiments previously described. The solutions in both cases appeared to have been saturated with respect to the slightly soluble salts.

During the latter part of the experiment, a vigorous growth of blue-green algae appeared upon the surface of the soil of the superphosphate plot, a less vigorous growth appeared upon the acid-phosphate soil, while no growth was noticed upon the control or upon the bone-meal soil. These algae are plants, and although of a lower order than barley and oats, they require phosphorus as a plant-food constituent. This growth upon the soil that had been treated with soluble phosphate was, therefore, very significant.

After 23 days of growth, a set of oat plants was taken from the thimbles, and analyzed for phosphorus. These results are given in Table IV.

TABLE IV.—ABSORPTION OF PHOSPHORUS FROM SOLUTIONS BY OAT SEEDLINGS.

	Grams phosphorus in 100 plants
1. Soil from control plot	.01047
2. Soil from bone-meal plot	.01058
3. Soil from 16% acid-phosphate plot	.01129
4. Soil from 44% superphosphate plot	.01307

It will be seen that the plants when grown in the thimbles, behaved very much like those that had been grown previously in the soil extracts, the plants grown in the superphosphate soil looked better and contained more phosphorus than did the others. The plants from the acid-phosphate soil were next best in appearance and next highest in phosphorus content, while the plants in the bone-meal soil grew no better and contained very little more phosphorus than did the control plants.

After 26 days of growth, a set of barley plants was withdrawn from the thimbles and analyzed for phosphorus.

TABLE V.—ABSORPTION OF PHOSPHORUS FROM SOLUTIONS BY BARLEY SEEDLINGS.

	Grams phosphorus in 100 plants
1. Control soil	.01296
2. Bone-meal soil	.01210
3. 16% acid-phosphate soil	.01297
4. 44% superphosphate soil	.01856

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These results, while probably not so definite as some of the others that have been given, indicate that the soil that had received an application of superphosphate had more phosphorus in its solution than did any of the others.

ANALYSES OF THE SOIL

An analysis of the soil from the control plot for total phosphorus was made by igniting a sample of the soil over a Bunsen burner, to destroy the organic matter, and digesting it with a mixture of hydrochloric and nitric acids. This treatment brought 0.0510 percent of phosphorus, or an equivalent of 0.1147 percent of P_2O_5 into solution. Upon the basis of dry soil, this percentage of phosphorus corresponds to about the average total phosphate content of soils in humid areas.

This soil from Bard which contains 0.1147 percent of P_2O_5, or an equivalent of about 4,500 pounds per acre-foot, would probably be classified by many as one that contains enough phosphorus to last ordinary crops many years.

Analyses of the water extracts of these soils were made by two methods. First, the soils were shaken with twice their weight of distilled water until the solutions came to equilibrium, filtered through porous filter cores, and analyzed for phosphorus. Second, 500 grams of each of the soils were placed in glass extraction tubes, percolated with 1 liter of distilled water, and the percolate analyzed for phosphorus. When calculated upon the basis of dry soil, the results were practically the same in both cases, and the average is shown in Table VI.

TABLE VI.—ANALYSES OF SOIL EXTRACTS.

	Parts per million of phosphorus in dry soil
1. Soil from control plot	0
2. Soil from bone-meal plot	0
3. Soil from 16% acid-phosphate plot	1.0
4. Soil from 44% superphosphate plot	2.0

Further percolations of the control and bone-meal soil failed to bring any phosphorus into solution, but the acid-phosphate and superphosphate soils continued to give up phosphorus, although in very small amounts.

From these analyses it seemed safe to assume that the soil solution in the control plot at Bard, is exceedingly low in phosphorus, and that the addition of phosphates in an insoluble form does not tend to bring any more phosphorus into solution. The so-called insoluble phosphates, floats, bone meal, etc., have each a definite solubility, they go into solution to the extent of a few parts per million, and should be available to plants in that concentration, yet under the conditions that exist at Bard and in many other places in the Southwest, the phosphate ion does not appear in the soil solutions.

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EXPERIMENTS WITH CULTURE SOLUTIONS OF LOW CONCENTRATIONS

When seedlings of wheat, oats, or barley are placed in solutions of low concentrations of plant food, they show that they are able to feed quite readily. This phenomenon is more marked in the case of potassium than it is with phosphorus, and it is, in many cases, hardly noticeable with nitrogen. In Table VII are shown the analyses of wheat, oats, and barley plants, that were grown for 20 days in the solutions of nitrogen as sodium nitrate, potassium as potassium chloride, and phosphorus as sodium phosphate. These solutions were changed every day. The analyses for phosphorus, alone, are given.

TABLE VII.—ABSORPTION OF PHOSPHORUS BY WHEAT, OAT, AND BARLEY SEEDLINGS.

	Grams phosphorus in 100 plants		
	Wheat	Oats	Barley
1. Control, distilled water	.0095	.0113	.0124
2. 1 p.p.m. each N.K. and P.	.0294	.0213	.0219
3. 2 p.p.m. each N.K. and P.	.0304	.0231	.0215
4. 10 p.p.m. each N.K. and P.	.0453	.0268	.0364
5. 25 p.p.m. each N.K. and P.	.0542	.0336	.0346
6. 50 p.p.m. each N.K. and P.	.0589	.0336	.0378
7. 100 p.p.m. each N.K. and P.	.0536	.0404	.0410

It will be seen that the absorption of phosphorus increased at a fairly uniform rate as the concentration of the nutrient solution was increased.

When the concentration was decreased even below one part per million of phosphorus, which is the only plant food now being considered, marked results were obtained. This has been shown several times with both oat and barley seedlings. It is true that in distinguishing between one-fourth and one-half parts per million of phosphorus, a large percentage of error may occur, yet there is no doubt but that plants do feed readily in these low concentrations. In Table VIII are shown the analyses of barley seedlings that were grown in low concentrations of plant food for 14 days.

TABLE VIII.—ABSORPTION OF PHOSPHORUS BY BARLEY SEEDLINGS FROM SOLUTIONS OF LOW CONCENTRATIONS.

	Grams phosphorus in 100 plants
1. Control, distilled water	.0112
2. ¼ p.p.m. each N.K. and P.	.0167
3. ½ p.p.m. each N.K. and P.	.0162
4. 1 p.p.m. each N.K. and P.	.0227
5. 10 p.p.m. each N.K. and P.	.0367

The results with oats were even more striking, as shown by the analyses of seedlings that were kept under observation for 11 days.

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TABLE IX.—ABSORPTION OF PHOSPHORUS BY OAT SEEDLINGS FROM SOLUTIONS OF LOW CONCENTRATIONS.

	Grams phosphorus in 100 plants
1. Control, distilled water	.01134
2. ¼ p.p.m. each N.K. and P.	.01620
3. ½ p.p.m. each N.K. and P.	.02190
4. 1 p.p.m. each N.K. and P.	.02527
5. 10 p.p.m. each N.K. and P.	.02826

It will be seen that, even in a concentration as low as ¼ of a part per million, the absorption of phosphorus was marked. Every day each of these culture pans was given 2,500 c.c. of water, containing a total of 0.005 gram of phosphorus in solution. The plants were able to extract all of the phosphorus, while transpiring only a few centimeters of water. This is a striking example of the ability of the plant to extract nutrient material from a solution without absorbing and transpiring very much water.

The absorption of phosphorus may be detected from concentrations as low as 1/10 part per million, provided that concentration is maintained. In Table X are shown the analyses of a control and of 34 oat seedlings that were grown in a solution of 1/10 part per million of phosphorus, for a period of 20 days. These 34 plants grew in 3 liters of culture solution containing a total of .0003 gram of phosphorus and the solutions were changed daily. Nitrogen and potassium in concentrations of about 20 parts per million each were also added every few days.

TABLE X.—ABSORPTION OF PHOSPHORUS FROM CULTURE SOLUTIONS OF LOW CONCENTRATIONS.

	Grams phosphorus in 34 plants
1. Control, distilled water	.00436
2. 1/10 parts per million of phosphorus	.00569

This experiment was repeated with similar results. There is no doubt but that a plant may feed in infinitely low concentrations of plant food, in fact there seems scarcely a limit to the possible dilution.

In the case of the Bard soil extract, therefore, if phosphorus had been present and available in concentrations as low as ¼, or even 1/10 of a part per million, the seedlings would have absorbed it. Evidently the untreated Bard soil does not give up an appreciable amount of phosphorus to an aqueous solution.

It is not doubted that the plants growing in this soil in the field, do absorb a certain amount of phosphorus from the soil solution. They must do this, or they would soon die. This phenomenon presents a problem upon which work is now being done. It seems as if the plant, in some way, can extract nutrient material from a soil, that would not otherwise

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be dissolved by the soil moisture. Whether this is due altogether to the exudation of carbon dioxide by the roots remains to be proved.

Plants are often known to respond to very small applications of fertilizers, and our experiments in the laboratory and in the field indicate that minute amounts of phosphorus may exert a very marked effect upon crops. However, as is well known, the effect of phosphorus upon vegetative development is not often marked during the first stages of growth. Phosphorus is more concerned with the formation of the seed or fruit, than it is with vegetative tissue.

Professor Franklin H. King often said that fertilizers seemed to act like certain medicines and that they were often effective in exceedingly small doses. He seemed to think that minute differences in the amounts of plant food in different soils might often account for their differences in productivity, and he was constantly asking chemists for methods that could be used in determining plant food accurately, in concentrations of less than a part per million. It seems to be a fact, that, under the conditions existing in many of the soils of the Southwest, phosphorus, at least, acts in homeopathic doses.

CARBON DIOXIDE IN THE SOIL SOLUTION

The experiments with insoluble phosphates, in the past, have been carried on almost exclusively in humid regions, and upon neutral or slightly acid soils. The soil from Bard, California, which is representative of many soils in the West, is calcareous, and has an alkaline reaction, showing that it contains free hydroxyl ions. These hydroxyl ions may be derived from calcium or other soluble bases, but they are often derived from sodium carbonate and indicate the presence of black alkali. The results obtained by Hopkins in Illinois, Thorne in Ohio, and others, are, therefore, not applicable to our southwestern conditions.

The soil atmosphere in the humid regions, especially when organic matter is present, is usually relatively high in carbon dioxide, and it is well known that carbon dioxide or carbonic acid in the soil solution exercises an important function in dissolving and bringing the slightly soluble plant foods into an available form.

The effect of carbon dioxide upon the availability of the phosphorus in floats and other slightly soluble phosphates, was determined. Wheat seedlings were grown in culture pans in the way that has been described in the presence of a slight excess of the treated and untreated phosphates. (See Table XI.) The phosphates were shaken each day with the culture solutions, and, as some of the solid material would adhere to the roots of the plant, the tops alone were used in the analyses. Soluble nitrogen and potassium also were added to these culture solutions in order to get

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vigorous plants. The seedlings were grown for 21 days, then ashed and analyzed for phosphorus.

TABLE XI.—EFFECT OF CARBON DIOXIDE UPON THE AVAILABILITY OF PHOSPHORUS IN FLOATS, TRI-CALCIUM PHOSPHATE, AND DI-CALCIUM PHOSPHATE.

No.	Treatment.	Grams phosphorus in 100 tops
1.	Control, distilled water	.0073
2.	Floats, shaken in culture solutions	.0095
3.	Floats, shaken with water and saturated with CO_2	.0115
4.	Phosphate made by dissolving floats in HCl, reprecipitating the phosphate with ammonia, and washing free from impurities. Used while wet	.0093
5.	Same as No. 4, except that the culture solution was saturated with CO_2	.0119
6.	Same as No. 4, except that phosphate was dried and ground fine, and used alone	.0096
7.	Same as No. 6, except that the solution was saturated with CO_2	.0106
8.	Phosphate made by precipitating calcium phosphate from a saturated solution of $CaSO_4$ with Na_2HPO_4, and ammonia, and washing free from impurities. Used while wet	.0120
9.	Same as No. 8, but phosphate dried and ground fine	.0102
10.	Same as No. 8, dried, ground fine, and solution saturated with CO_2	.0124
11.	Phosphate made by dissolving calcium carbonate, $CaCO_3$ in HCl, adding Na_2HPO_4 and ammonia, and washing until pure. Used while wet	.0115
12.	Same as No. 11, but solution saturated with CO_2	.0127
13.	Five parts per million of phosphorus as mono-calcium phosphate	.0126

These results show the effect of carbon dioxide upon the tri- and di-calcium phosphates. The phosphorus of the mono-calcium phosphate, No. 13, is readily soluble in water and available in low concentrations. The floats, No. 2, represent the tri-calcium or insoluble, while the phosphate used in numbers 4 and 5, represents the di-calcium or reverted form. It will be seen that the effect of carbon dioxide is shown in every case. Experiments similar to the above were conducted with barley seedlings with equally conclusive results. It should be borne in mind that while the culture solutions were saturated daily with carbon dioxide, they stood in open pans for 24 hours and some of the gas was doubtless lost.

THE EFFECT OF CARBON DIOXIDE UPON THE AVAILABILITY OF PHOSPHORUS IN BONE ASH

A sample of ignited bone ash was washed free from soluble impurities, and small amounts of this solid were added to water cultures as described in Table XII. The plants were kept under observation for 15 days and their analyses are shown in the table.

TABLE XII.—THE EFFECT OF CARBON DIOXIDE UPON THE AVAILABILITY OF PHOSPHORUS IN BONE ASH.

No.	Treatment	Grams phosphorus in 100 tops
1.	Control, distilled water	.0063
2.	Solid bone ash shaken daily with solution of 50 p.p.m. Na_2CO_3	.0114
3.	Solid bone ash shaken with water and saturated daily with CO_2	0161

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The addition of sodium carbonate to No. 2 was made, not for the purpose of its solubility effect upon the bone ash, nor in order to have a toxic body present. Sodium carbonate in the concentration used, is a stimulant to plants, and we often add it in small amounts to water cultures, when good plants are desired. In this experiment the plants receiving sodium carbonate were decidedly better and had a better root development than did those grown in the carbon dioxide solution, yet they did not contain as much phosphorus. Roots of growing plants exude carbon dioxide and if this gas had been present in solution in culture No. 2, it would have had an effect, although probably small, upon the solid bone ash. The sodium carbonate was, therefore, added in order to keep this exuded carbon dioxide out of solution, and only enough was used to accomplish this purpose. The sodium carbonate, when first added to the culture solution, gave a color with phenolphthalein, indicating an hydroxyl-ion concentration, but this color would become more and more faint, due to the conversion of the sodium carbonate into bicarbonate, until the next day when no color was obtained. It may be said, therefore, that the sodium carbonate fulfilled its mission and kept the carbon dioxide out of solution. The difference in the phosphorus content of the plants in culture 3 over that of culture 2, can, therefore, be safely attributed to the effect of carbon dioxide upon the insoluble bone ash.

CARBON DIOXIDE NOT ALWAYS PRESENT IN THE SOIL SOLUTION

We have shown that carbon dioxide, in solution, will bring insoluble phosphates into an available form. We are taught, furthermore, that carbon dioxide exists in the soil atmosphere in relatively large amounts, especially when decomposing organic matter is present. If carbon dioxide exists in these soils and in the soil solutions under field conditions, it is reasonable to assume that it would exert an effect upon the insoluble phosphates in the soil and bring some phosphorus into solution. The assumption that carbon dioxide exists in all soils, however, may be unwarranted.

Attention has been called to the fact that the soils under consideration are calcareous and contain a little black alkali, and thus have free hydroxyl ions in the soil solution. It is impossible to conceive of sodium carbonate, with its free hydroxyl ions, and carbon dioxide, or carbonic acid, existing in the same solution, so we are forced to the conclusion that these soils contain little or no carbon dioxide, either in the soil solution or in the soil atmosphere. Black alkali soils cannot contain an appreciable amount of carbon dioxide, and, as a reverse, soils that contain carbon dioxide cannot

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contain black alkali.* In a black alkali soil, therefore, the effect of carbon dioxide upon the insoluble phosphates is reduced to a minimum, if any such action exists at all, and plants may actually suffer for phosphorus in a soil that is rich in that element.

EXPERIMENTS WITH CALCAREOUS SOILS AND CARBON DIOXIDE

A sample of Bard soil which contained .051 percent of phosphorus in insoluble form, but no soluble phosphorus, was mixed with twice its weight of water, (1,000 grams soil—2,000 c.c. of water), and this mixture saturated daily with carbon dioxide. The mixture was shaken in a machine after the addition of carbon dioxide, allowed to stand overnight, the extract decanted but not filtered, and a set each of barley and oat seedlings were grown in the extract. The extracts were used over and over again, that is, the solutions were allowed to stand in contact with the soil one day and used in the culture pans the next, while the extract that the plants had grown in on one day would be poured back into the bottle, saturated with carbon dioxide, and allowed to stand until the next day. One hundred parts per million of nitrogen, as sodium nitrate, were added to the culture solutions in three different applications.

TABLE XIII.—EFFECT OF CARBON DIOXIDE UPON THE AVAILABILITY OF PHOSPHORUS IN A CALCAREOUS SOIL.

No.	Treatment	Grams phosphorus in 100 plants	
		Barley	Oats
1.	Extract of untreated soil control	.01301	.01339
2.	Extract saturated daily with carbon dioxide	.01215	.00978

These experiments gave results opposed to those that were expected at the time, that is, they indicated that the presence of carbon dioxide in calcareous soil solutions would tend to diminish rather than to increase the availability of the phosphates.

CARBON DIOXIDE NOT EFFECTIVE IN CALCAREOUS SOILS

If insoluble phosphates, when applied to neutral or acid soils, produce beneficial effects, and if these effects are due largely to the presence of carbon dioxide in the soil, it would seem as if western soils which contain no black alkali, should respond to applications of insoluble phosphates, assuming that an excess of carbon dioxide is dissolved in the soil solution. However, we have at hand no data which prove that applications of floats to western calcareous soils, even when accompanied by applications of manure, produce beneficial results. This failure is due probably to the presence of

*Breazeale, J. F. & Burgess, P. S. Technical Bulletin No. 6, Ariz. Agri. Exp. Sta., "The Reaction between Calcium Sulphate and Sodium Carbonate, and its Relation to the Reclamation of Black Alkali Lands."

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calcium carbonate, which keeps the carbon dioxide out of solution. What is true as to the presence of carbon dioxide in a black alkali soil, is also true, in a lesser degree, in a soil containing an excess of calcium carbonate. When carbon dioxide is generated in a calcareous soil, it is dissolved by the soil moisture with the formation of carbonic acid, which dissolves calcium carbonate and brings calcium bicarbonate into solution. While this reaction between calcium carbonate and carbonic acid may not run completely to an end, it certainly is effective in keeping carbonic acid out of solution until the soil solution is practically saturated with calcium bicarbonate.

AVAILABILITY OF PHOSPHORUS IN FLOATS, IN THE PRESENCE OF CARBON DIOXIDE, CALCIUM CARBONATE, AND CALCIUM SULPHATE

Cultures of barley were grown for 16 days in the solutions that are described in Table XIV. The solutions were first placed in large bottles and were saturated daily with carbon dioxide. The solutions were allowed to stand 24 hours in order that the sediments might settle, and the clear liquids were then decanted into the culture pans. In this method, the plants came in contact with the solution only, and not with floats, calcium carbonate, or calcium sulphate in solid phase.

TABLE XIV.—AVAILABILITY OF PHOSPHORUS IN THE PRESENCE OF CARBON DIOXIDE, CALCIUM CARBONATE, AND CALCIUM SULPHATE

No.	Treatment of solution	Grams phosphorus in 100 plants
1.	Control, distilled water	.01280
2.	Floats, saturated daily with carbon dioxide	.01512
3.	Floats with calcium carbonate saturated daily with carbon dioxide	.01210
4.	Floats with excess calcium sulphate, saturated daily with carbon dioxide	.01557

The plants that grew in the solutions containing calcium carbonate, No. 3, were found to contain even less phosphorus than did those that grew in the distilled water. The difference is probably within the limits of error of the experiment, yet it is clear that carbon dioxide in the presence of calcium carbonate had brought no phosphorus into solution. There was considerable increase in the phosphorus content of the plants in solution No. 2 where floats occurred alone, and saturated daily with carbon dioxide. The plants in the cultures containing calcium sulphate also showed a decided increase in their phosphorus content.

SOLUBILITY OF FLOATS IN SOLUTIONS OF CARBON DIOXIDE, CALCIUM CARBONATE, AND CALCIUM SULPHATE

Heretofore our experiments have dealt largely with the available rather than with the soluble phosphorus. Some experiments were now made

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upon the solubility of floats in solutions of carbon dioxide, calcium carbonate, and calcium sulphate.

Two grams of floats and 2,000 c.c. of water were placed in each of five bottles and treated as shown in Table XV. The bottles were shaken at intervals for 2 days, allowed to stand overnight, the solutions filtered through filter papers and 1,000 c.c. of each evaporated to a small volume and analyzed for phosphorus.

TABLE XV.—SOLUBILITY OF FLOATS IN SOLUTIONS OF CARBON DIOXIDE, CALCIUM CARBONATE, AND CALCIUM SULPHATE.

No.	Treatment	Parts per million in solution	
		Ca	P
1.	Floats in carbon-dioxide-free water	1.5	.30
2.	Floats in water saturated with carbon dioxide	31.5	4.48
3.	Floats in carbon-dioxide-free water with excess of calcium carbonate	19.5	.23
4.	Floats with excess of calcium carbonate saturated with carbon dioxide	322.0	Trace
5.	Floats with excess of calcium sulphate saturated with carbon dioxide	637.0	3.33

The floats used in the control had been washed free from calcium carbonate with dilute nitric acid, yet more calcium went into solution than that required to balance the phosphorus in the formula $Ca_3(PO_4)_2$. This indicates the presence of other salts of calcium in the floats.

It will be seen from the table that the solubility of phosphorus in floats in distilled water, was increased 15 times by the addition of carbon dioxide to the solution. The presence of calcium carbonate alone, No. 3, did not materially affect the solubility of the phosphorus. When carbon dioxide was introduced into the solution containing floats and calcium carbonate, No. 4, it brought 322 parts per million of calcium into solution which forced the phosphorus existing as tri-calcium phosphate, almost completely out of solution. In a saturated solution of calcium sulphate and carbon dioxide, No. 5, while the solubility of the phosphorus was slightly reduced from that obtained with carbon dioxide alone, the solution contained about 12 times as much as did the control. These reactions will be discussed later.

The solubilities of the slightly soluble phosphates under the conditions just described, are in accordance with chemical laws, and the solubilities were all indicated in advance by the behavior of the seedlings in the experiments that have been described. Our results correspond fairly well with those of Cameron and Seidel.*

*Jour. Amer. Chem. Soc. 26:1454, 1904.

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TRI-CALCIUM PHOSPHATE AND CARBON DIOXIDE

It is common agricultural practice, where available phosphorus is low, to apply floats or finely ground, steamed bone meal to the neutral or slightly acid soils of the humid regions, where considerable quantities of organic matter are present. Such applications are usually beneficial. The explanation commonly offered is that the carbon dioxide evolved during the decomposition of the organic matter changes the inert tri-calcium phosphate into more available forms. This action is well illustrated in Table XIV where the solubility of tri-calcium phosphate was raised from less than 1 p.p.m. of phosphorus to nearly 5 p.p.m. by the addition of carbon dioxide alone. The reaction may be represented as follows:

$$Ca_3(PO_4)_2 + 2H_2CO_3 \leftrightarrows Ca_2H_2(PO_4)_2 + Ca(HCO_3)_2$$

This equation is but slightly reversible under field conditions, i. e., di-calcium phosphate does not react with calcium carbonate to form tri-calcium phosphate and carbonic acid. In our studies it was found that, at approximate equilibrium, 4.48 p.p.m. of phosphorus were brought into solution by carbon dioxide. While in field soils probably less would be dissolved, nevertheless, sufficient carbon dioxide is usually present, under humid conditions, to bring sufficient phosphate into solution to produce marked effects upon crop growth if tri-calcium phosphate is present.

The reaction above cited represents the action of carbonic acid upon tri-calcium phosphate, providing it had the molecular formula, $Ca_3(PO_4)_2$, but probably very few naturally occurring phosphates have their phosphate and lime present in exactly these proportions. According to most authorities, rock phosphate is in reality a series of solid solutions of di-calcium phosphate, and calcium oxide, and in varying proportions, together with other materials (often calcium carbonate). When such solid solutions come in contact with pure water or with water charged with carbon dioxide, the resulting aqueous solutions carry an excess of phosphoric acid or base depending upon the composition of the rock.* The solid solution thus goes into true aqueous solution as di-calcium phosphate and calcium bicarbonate. In the presence of a great excess of the latter more soluble salt, however, much less of the phosphate will be dissolved due to the "common-ion effect." This has been found to be the case in our solubility studies. As is well known, tri-calcium phosphate is of little value as a source of phosphorus to plants when acting alone. It must first be changed to the more available mono- or di-calcium form, either by carbonic acid or by means of stronger acids, before it is of value.

*It has been found that the phosphate ion is more rapidly leached from these solid solutions than is the lime, hence as time goes on and leaching progresses, the naturally occurring phosphate becomes more and more basic and increasingly insoluble. See, "The Action of Water and Aqueous Solutions Upon Soil Phosphates" by Cameron and Bell, Bul. 41, Bureau of Soils, U. S. D. A., for an extensive discussion of this subject.

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TRI-CALCIUM PHOSPHATE, CALCIUM CARBONATE, AND CARBON DIOXIDE

The reactions above discussed might be expected to take place in neutral or slightly acid soils containing little solid calcium carbonate. The soils of the Southwest, however, usually carry from 1 to 10 percent of calcium carbonate, and occasionally much more. Conditions here, therefore, are decidedly different. The addition of calcium carbonate to an aqueous suspension of floats has little effect upon the solubility of the phosphate, as shown in Table XIV, but when carbon dioxide is introduced into the suspension an entirely different set of conditions prevails. This reaction may be represented as follows:

$$Ca_3(PO_4)_2 + CaCO_3 + H_2CO_3 \leftrightarrows Ca_3(PO_4)_2 + Ca(HCO_3)_2$$

It has been found that the tri-calcium phosphate does not enter appreciably into this reaction, hence practically no phosphorus is brought into solution. Carbonic acid is a weak acid, hence when present with a mixture of calcium phosphate and calcium carbonate, the action is entirely with the latter, more basic salt. As long as calcium carbonate is present, no attack will be made upon the tri-calcium phosphate. Kelley also has shown this to be true for the nitrous and nitric acids biologically formed in calcareous soils.

The solubility of calcium bicarbonate is over 1,000 p.p.m. in pure water, while that of tri-calcium phosphate is extremely low. Thus, in a solution containing both, we would expect to find less soluble phosphorus than in one carrying tri-calcium phosphate alone. This is shown to be the case in Table XIV.

In field practice, the beneficial effects of applications of floats and organic matter to neutral or acid soils and the absolute lack of response to such treatments in calcareous soils are explained. The addition of organic matter (carbonic acid) with the floats in the latter case (see Table XIV) tends actually to decrease, rather than increase, the slight solubility of the phosphate.

TRI-CALCIUM PHOSPHATE, GYPSUM, AND CARBON DIOXIDE

Where floats is applied to a neutral soil containing gypsum and carbon dioxide, another set of conditions prevails. In our experiments, floats and gypsum were suspended in pure water which was kept saturated with carbon dioxide, and shaken for several days until an approximate equilibrium had been attained. The carbonic acid had practically no effect upon the solubility of the gypsum but did react to a limited extent with the tri-calcium phosphate. The equation may be represented as follows:

$$Ca_3(PO_4)_2 + CaSO_4 + 2H_2CO_3 \leftrightarrows Ca_2H_2(PO_4)_2 + CaSO_4 + Ca(HCO_3)_2$$

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The gypsum present in solution, carrying the common calcium ion, had a slight tendency to retard the solution of the tri-calcium phosphate. This effect is shown in solutions No. 2 and No. 5 of Table XIV. As the tri-calcium phosphate has a marked solubility in carbonic acid solutions, and as gypsum does not take up carbonic acid on dissolving, the retarding effect of the latter salt is but slight.

SOLUBLE PHOSPHATE APPLICATIONS TO CALCAREOUS SOILS

Our experiments confirm Hilgard's early statements that, in western calcareous soils, plants usually respond to applications of soluble phosphates, while showing no response to the insoluble tri-calcium form. The water-soluble, mono-calcium phosphate will remain in solution only in the presence of an excess of hydrogen ions. It is well known that, when this phosphate is added to a soil containing calcium carbonate or other basic material, it quickly reverts to the most insoluble form which it is capable of assuming under these conditions. The reaction may be written as follows:

$$CaH_4(PO_4)_2 + 2CaCO_3 \leftrightarrows Ca_2H_2(PO_4)_2 + Ca(HCO_3)_2$$

This reaction quickly runs to completion from left to right, and is but slightly reversible. Di-calcium phosphate, furthermore, is stable in the presence of an excess of calcium carbonate, and does not go over into the tri-calcium form. Now, as di-calcium phosphate is slightly soluble in water, we would expect that an application of any soluble phosphate (acid phosphate or double superphosphate) would be beneficial to a calcareous soil. Field experience has shown this to be true.

AVAILABILITY OF PHOSPHATES IN THE PRESENCE OF IRON AND ALUMINUM

All soils contain oxides, or hydrated oxides, of iron and aluminum, and it has been a matter of much speculation as to the effects which these materials have upon the availability of soil phosphorus. It is known that iron and aluminum phosphates are much less soluble in water than is the so-called tri-calcium phosphate; also, that a mixture of slightly soluble substances approaching equilibrium conditions in a water solution at constant temperature, follows certain definite chemical laws. Such a heterogeneous equilibrium, as between tri-calcum phosphate, ferric hydroxide, and carbon dioxide in pure water, involves both solution and reprecipitation. If a solid is in contact with its saturated solution (partially or wholly ionized), and the ion product is in any way lowered by the removal of either ion from solution, more of the solid will dissolve, and enter into reaction until the substances finally resulting are the most insoluble

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possible combinations of the ions involved. Thus, if floats and organic matter are added to a non-calcareous soil containing hydrated oxides of iron, carbon dioxide will be evolved as decomposition progresses, and we may expect a reaction taking place within the soil solution between these compounds. Tri-calcium phosphate is soluble to the extent of 3 or 4 p.p.m., ferric hydroxide less than 1 p.p.m., while carbon dioxide in cold water is soluble to the extent of over 1,000 p.p.m. Due to these differences in solubility, the tri-calcium phosphate will be fairly rapidly dissolved as di-calcium phosphate while the ferric hydroxide will be but slowly attacked. The following reactions may represent such changes:

$$Ca_3(PO_4)_2 + 2Fe(OH)_3 + 6H_2CO_3 \leftrightarrows 3Ca(HCO_3)_2 + 2FePO_4 + 6H_2O$$

It is thus very probable that, in non-calcareous soils, some of the phosphates added, either as mono-, di-, or tri-calcium phosphate, enter into combination with iron or aluminum if not first taken up by plants, and we are led to believe that the phosphorus in soils, which is insoluble in carbonated water, but soluble in the stronger mineral acids, exists largely as iron or aluminum phosphates.

The apparent insolubility of the iron and aluminum phosphates has contributed to the belief that their phosphorus is largely lost to the plant. However, it has been repeatedly shown that *artificially prepared* iron and aluminum phosphates are available sources of this element for plants, while, for reasons that have not yet been explained, the finely ground, *naturally occurring* phosphates of these metals are almost wholly unavailable. Two definite reasons for this apparent anomaly present themselves:

First: The precipitated compounds are much more finely divided and expose a much greater surface to the action of the solvent. Thus, while *at equilibrium* the same amounts of phosphorus may be rendered soluble from both sources, the actual *rate* at which solution progresses may be many times greater in the case of the finely divided, precipitated materials. Professor F. H. King, many years ago, while in the Federal Bureau of Soils, accumulated many data which indicated that the *rate* of solution of the more insoluble plant nutrients is of far more importance to the growing plant than are *the absolute amounts* of these substances which may be dissolved from a soil when equilibrium conditions between it and the solvent are approached.

Second: The action of water and carbonated water upon the phosphates of iron and aluminum is similar to that of like solutions upon the phosphates of calcium, although somewhat slower. When aqueous solutions come in contact with all of these phosphates, the phosphate ion is removed more rapidly than is the calcium ion, resulting in the formation

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of a more basic residue. The basic phosphates are thus more insoluble than are the neutral phosphates, and in the naturally occurring minerals which have been leached for ages, these basic phosphates greatly predominate. On the other hand, freshly precipitated ferric phosphate invariably contains an excess of phosphate ions over that required to form $FePO_4$.* It is thus acidic rather than basic, and hence much more soluble and available.

In order to study the reactions taking place between floats, ferric hydroxide and calcium carbonate when suspended in carbonated water, several large bottles were prepared as indicated in Table XVI. The ferric hydroxide used was the mineral limonite, ground to an impalpable powder in a ball mill. Two grams of each of the solids indicated in the table were added to 2 liters of cold water saturated with carbon dioxide, and shaken intermittently, with additions of carbon dioxide, over the periods stated. One liter of each solution was evaporated and analyzed for phosphorus.

TABLE XVI.—SOLUBILITY OF FLOATS IN THE PRESENCE OF FERRIC HYDROXIDE, CALCIUM CARBONATE, AND CARBON DIOXIDE.

No.	Treatment	Parts per million of phosphorus in solution	
		After 18 hours	After 12 days
1.	Floats in solution saturated with carbon dioxide	2.03	2.70
2.	Floats, with ferric hydroxide in solution, saturated with carbon dioxide	1.28	.88
3.	Floats with calcium carbonate, in solution saturated with carbon dioxide	Trace	00

As here shown, floats is soluble to the extent of about 10 p.p.m. in water saturated with carbon dioxide. It is also evident that all of this soluble phosphorus has not been removed as the insoluble ferric phosphate (No. 2) at the end of the 12-day period. Under humid soil conditions, where organic matter is present, the carbonic acid will progressively react with the tri-calcium phosphate to maintain soluble phosphorus in the soil solution at all times, even though some may be slowly precipitated, possibly as the basic ferric phosphate. This action will continue as long as any tri-calcium phosphate remains in the soil.

In a calcareous soil, however, the carbonic acid reacts first with the calcium carbonate rather than with floats as we have previously shown, and

*An excellent discussion of this subject appears in Bul. 41, Bureau of Soils, U. S. D. A., "The Action of Water and Aqueous Solutions upon Soil Phosphates," by Cameron and Bell.

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we have a soil solution partially saturated with calcium bicarbonate. This will prevent any action on the tri-calcium phosphate, so that no reaction can be expected between it and the hydroxides of either iron or aluminum. This effect is shown in No. 3, Table XVI.

The hydrated oxides of iron exist in considerable quantities in all soils while *soluble* phosphorus is usually present in extremely small amounts. The relative solubilities of ferric hydroxide and ferric phosphate will determine the possibility of the formation of the latter compound in soils. Both are extremely insoluble in pure water, and even less soluble in alkaline solutions. Hence we may expect no reaction whatever in calcareous soils, where hydroxyl ions are always present in excess.

PRECIPITATION OF PHOSPHORUS FROM SOLUTION BY FERRIC HYDROXIDE WHEN NO CARBON DIOXIDE IS PRESENT

A solution containing .00655 gm. per 100 c.c., or 65.5 p.p.m. of phosphorus was prepared by shaking a small amount of commercial superphosphate with an excess of calcium carbonate, allowing the mixture to stand for three days, and filtering off the clear solution. The phosphorus in this solution was largely in the form of reverted, or di-calcium phosphate.

One liter of this solution was placed in a bottle, and 1.5 grams of finely pulverized limonite added. The solution was allowed to stand for 24 hours with occasional shaking, and 100 c.c. were filtered off and analyzed for phosphorus. The solution was then shaken and allowed to stand for 1 day more and analyzed again for phosphorus. This was continued for 7 days, and the results of the analyses are shown in Table XVII.

TABLE XVII.—PROGRESSIVE REMOVAL OF SOLUBLE PHOSPHORUS FROM SOLUTION BY LIMONITE.

No.		Grams phosphorus in each 100 c.c. solution
1.	Original solution	.00655
2.	After standing 1 day in contact with ferric hydroxide	.00634
3.	After standing 2 days in contact with ferric hydroxide	.00624
4.	After standing 3 days in contact with ferric hydroxide	.00620
5.	After standing 4 days in contact with ferric hydroxide	.00605
6.	After standing 5 days in contact with ferric hydroxide	.00591
7.	After standing 6 days in contact with ferric hydroxide	.00577
8.	After standing 7 days in contact with ferric hydroxide	.00570

It will be seen that, after standing in contact with the solution of di-calcium phosphate of a concentration of 65.5 p.p.m. of phosphorus for 7 days, the ferric hydrate had removed only 8.5 p.p.m of phosphorus from solution. This concentration of phosphorus (65.5 parts per million) is

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probably 20 times as great as that ordinarily found in the soil solution. In a concentration of 1 or 2 p.p.m. of phosphorus the reaction with ferric hydrate thus must be *exceedingly slow*.

The reaction just described took place in a solution that contained neither carbon dioxide nor an excess of calcium carbonate. The presence of these two compounds would have prevented even this slow reaction between the phosphate and the ferric hydroxide.

COMPETITION BETWEEN PLANTS AND FERRIC HYDROXIDE FOR SOLUBLE PHOSPHORUS

Knowing that ferric hydroxide slowly removes phosphorus from solution, especially in non-calcareous soils, and also knowing that plants absorb phosphorus from solution, it is evident that a competition must exist in many soils between plants and ferric hydroxide for this element. It has been shown that growing seedlings make a strong demand for phosphorus, that they are vigorous feeders, and that they are able to feed in extremely low concentrations.

A determination of the ability of barley seedlings to compete with ferric hydroxide for phosphorus was shown in the following experiment. Six solutions of 2 liters each, were prepared from commercial superphosphate, and treated as indicated in Table XVIII. Two of these solutions contained phosphorus and ferric hydroxide but no plants, two contained phosphorus alone with 100 barley seedlings, while the other two contained both phosphorus and ferric hydroxide with 100 barley plants. The experiment lasted 7 days, and the amount of phosphorus which remained in solution at the end of that period is shown in Table XVIII.

TABLE XVIII.—COMPETITION BETWEEN BARLEY SEEDLINGS AND FERRIC HYDROXIDE FOR SOLUBLE PHOSPHORUS.

No.	Treatment	Parts per million of phosphorus	
		Added	F'd in solution
	Without plants		
1.	Solution of calcium phosphate shaken with 1 gm. of limonite	5 57	4 95
2.	Solution of calcium phosphate shaken with 1 gm. of limonite	2 79	2 73
	With plants		
3.	Solution of calcium phosphate with 100 barley seedlings	5 57	27
4.	Solution of calcium phosphate with 100 barley seedlings	2 79	"
5.	Solution of calcium phosphate with 1 gm. limonite and 100 barley seedlings	5 57	0
6.	Solution of calcium phosphate with 1 gm. limonite and 100 barley seedlings	2 79	0

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It will be seen that ferric hydroxide removed only .62 part per million of phosphorus from solution No. 1 which originally contained 5.57 parts per million, and practically no phosphorus from solution No. 2 which contained 2.79 parts per million. At the same time 100 barley seedlings removed nearly all, or 5.3 parts per million of phosphorus from the solution that contained 5.57 parts per million, and all from the solution that contained 2.79 parts per million, while all of the phosphorus was removed from solution in the cultures containing both the plants and the ferric hydroxide.

It is evident that when a solution of soluble phosphorus is placed in contact with ferric hydroxide in the presence of growing plants under conditions represented by the above experiment, the absorption of phosphorus by the plants is a great deal more rapid than is the precipitation as insoluble ferric phosphate. When one considers the rapidity with which most plants feed, and the extreme slowness of the reaction between the soluble phosphates and the ferric hydroxide, there can be no doubt but that, under field conditions, the odds are greatly in favor of the plant in its competition for phosphorus with ferric or aluminum hydroxide.

COMPETITION FOR PHOSPHORUS IN NEUTRAL OR ACID SOILS

In an acid soil, or in a soil containing carbon dioxide but no calcium carbonate, conditions are somewhat different from those just described. Ferric hydroxide is slightly more soluble than is ferric phosphate in weak acids, so that the reaction between calcium phosphate and ferric hydroxide under such conditions should go on more rapidly, and this is indicated by the following experiment.

TABLE XIX.—COMPETITION BETWEEN FERRIC AND ALUMINUM HYDROXIDES AND BARLEY SEEDLINGS FOR SOLUBLE PHOSPHORUS IN THE PRESENCE OF CARBON DIOXIDE.

No.	Treatment	Grams phosphorus in 100 plants
1.	Control, distilled water	.01280
2.	Floats saturated with carbon dioxide	.01512
3.	Floats and ferric hydroxide saturated with carbon dioxide	.01242
4.	Floats with aluminum hydroxide saturated with carbon dioxide	.01296

Cultures of barley were grown for 16 days in the solutions described in Table XIX, and then analyzed for phosphorus. The solutions that contained the floats, and the floats plus ferric hydroxide or aluminum hydroxide (Nos. 2, 3, and 4), were placed in large bottles, saturated with

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carbon dioxide, and allowed to stand for 24 hours. The clear solutions were then decanted into culture pans that contained the barley seedlings, and the solutions changed daily. In this way the plant roots did not come in contact with the solid floats or with solid ferric or aluminum hydroxides. Phosphorus that was brought into solution by the carbon dioxide from the floats, stood in contact with the finely divided ferric and aluminum hydroxides for 24 hours before the plants were put into the solutions. From the results of this experiment, the phosphorus seems to have been largely removed from solution during this time by the iron or aluminum salts, as no increase in the phosphorus content of the plants in cultures Nos. 3 and 4 was noted.

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CONCLUSIONS

1. Neutral or acid soils in humid regions often respond to applications of floats, or insoluble phosphates, especially if there is an abundance of organic matter present.

2. Calcareous or alkaline soils in semi-arid regions do not respond to applications of insoluble phosphates, although they do respond to the soluble acid phosphates.

3. Certain western calcareous soils which have been fertilized with floats or bone meal, yield water extracts which contain little or no phosphorus, while such soils which have been fertilized with acid or superphosphates yield extracts which contain appreciable amounts of phosphorus.

4. Plants are able to absorb phosphorus readily from solutions as dilute as one-tenth of a part per million.

5. The presence of CO_2 in solution increases the solubility and availability of the phosphorus in both tri-calcium and di-calcium phosphates.

6. In western soils that contain black alkali, there is no free CO_2, so that in such soils the solvent action of CO_2 upon the insoluble phosphates is eliminated.

7. Floats is practically insoluble in carbon-dioxide-free distilled water and in carbon-dioxide-free water containing an excess of $CaCO_3$.

8. Floats in a saturated solution of CO_2 has a relatively high solubility, while in a saturated solution of CO_2 with $CaCO_3$, or $Ca(HCO_3)_2$, it is practically insoluble.

9. Floats in a saturated solution of CO_2 with $CaSO_4$ has an appreciable solubility, but slightly lower than in the absence of $CaSO_4$.

10. Tri-calcium phosphate alone seems to be of little value as a source of phosphorus to the plant.

11. The beneficial effect of the application of floats to eastern soils which contain decomposing organic matter, or CO_2, is due largely to the fact that the CO_2 changes the tri-calcium phosphate to di-calcium phosphate and thus renders the phosphorus available.

12. The lack of response of western calcareous or alkaline soils to applications of floats or bone meal is due chiefly to the fact that under these conditions there is no CO_2 to react with the tri-calcium phosphate as carbonic acid will react first with the more basic $CaCO_3$, or Na_2CO_3 if present.

13. The beneficial effects of applications of soluble phosphates to western soils are accounted for largely by the fact that, under these conditions, mono-calcium phosphate will revert to the di-calcium form which is available, but not to the tri-calcium or insoluble form.

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14. The application of manure to western calcareous soil, while advisable from other considerations, will tend to decrease rather than increase the availability of the insoluble tri-calcium phosphates.

15. Ferric and aluminum hydroxides react slowly with calcium phosphate and form insoluble ferric and aluminum phosphates. This action is accelerated by the presence of carbonic acid alone, but retarded by carbonic acid plus calcium carbonate.

16. After an application of calcium phosphate to a soil, there is competition for the phosphate between the growing plants and the ferric and aluminum hydroxides. In a neutral soil containing no carbonic acid, in a black alkali soil, or in a soil containing an excess of calcium carbonate plus carbonic acid, the odds are greatly in favor of the plants. In a slightly acid soil, or in a soil containing carbonic acid but no calcium carbonate, the plants will have more difficulty in absorbing the phosphorus before it enters into combination with the iron and aluminum.

17. Explanations are offered as to why artificially precipitated iron and aluminum phosphates are more available sources of phosphorus than are the naturally occurring mineral phosphates of these metals.

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ALKALI TOLERANCE OF PLANTS CONSIDERED AS A PHENOMENON OF ADAPTATION

By J. F. Breazeale

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FOREWORD

When an investigator of plant behavior observes an oft-repeated but somewhat obscure natural phenomenon, his first thoughts are, why is this and what is its underlying cause? In the absence of definite data, the tendency too often has been to formulate explanatory theories which do not explain, but rather tend to befog the issue. Almost invariably too hard work is made in attempting to explain a comparatively simple life process, the ultimate desire being usually to formulate definite mathematical expressions for bio-phenomena which of necessity under natural conditions vary as conditions vary, and hence we have such meaningless terms as "physiologically balanced nutrient solutions," "antagonism," and "the damming-out effect" of one ion for another.

The more simple the explanations and the less involved the contributing theories invoked, the more plausible do they become. The author of this bulletin gives us a straightforward, logical reason why plants tolerate more of one alkali salt than of another, and why plants vary among themselves in resistance to alkali poisoning; also why the calcium ion almost invariably has an ameliorating effect when concomitantly present, and why other ions do not. With plants, as with animals, we realize that there are certain fundamental traits that are fixed, while other more or less superficial characteristics may be changed almost at the will of the plant breeder, and within a few generations. Examples of the former are: The necessity for the 10 or 12 essential elements present in true solution and in ionic forms; the tendency of most plants to grow in a vertical position and with the leaves flat toward the sun; the tendency to grow toward the light, etc. Examples of changeable properties are, high or low fat, protein, or carbohydrate contents of fruits, and certain other flowering and fruiting propensities. The fixed characteristics are those which have been slowly formed during the untold ages through which the plant has passed in becoming adapted to present external, environmental conditions. The superficial characteristics have been more a matter of chance and are of less importance to the plant from the very essential viewpoint of propagation.

The paper which follows is unique in that it offers an explanation of alkali tolerance not heretofore generally considered.

P. S. Burgess,
Agricultural Chemist.

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ALKALI TOLERANCE OF PLANTS CONSIDERED AS A PHENOMENON OF ADAPTATION

By J. F. Breazeale

INTRODUCTION

In popular conception, the term "alkali" carries with it the idea of the salts of sodium, together with and in small amounts, the salts of calcium and magnesium. It is true that of all the alkalies occurring in the soil, sodium salts are the most common, but there are many salts that may be considered as alkalies, other than the salts of sodium, calcium, and magnesium. Copper sulphate, for example, existing in small amounts, is just as much an alkali as is sodium chloride, and although not in evidence as an alkali crust, it is capable of doing much harm. In this bulletin the term "alkali" is used to designate any water-soluble salt in the soil.

When certain salts, sodium chloride or magnesium sulphate, for example, are added to soil or water cultures of most plants in increasing amounts, a concentration will be reached in which the plants will not grow. This concentration has been termed the "limit of endurance" or "alkali tolerance" of the plant, and this varies widely with plants of different species, and also, to a much less degree, with individuals of the same species. In western soils, where all the alkalies occur, and in different percentages, it is a matter of great importance to know what crop is best suited for growing in each alkali soil, or in each percentage of alkali. An accurate determination of the alkali tolerance of certain plants for the common salts is, therefore, of far-reaching importance economically, and so the energies of many investigators have been bent in this direction. This phase of alkali tolerance, that is, its relation to crop production, will not be discussed here. This bulletin is concerned with some of the essential reasons why plants react as they do when brought in contact with a more or less toxic salt.

To one who has worked on the subject of alkali in its relation to plant growth, and who has studied the literature on the subject, the lack of correlation in the work of investigators along this line is striking. It is almost impossible to repeat the work of another person and get comparable results. This lack of correlation is usually attributed to one of two causes—unskilled workmanship and too many variants. While these two factors unquestionably have played an important part in past investigations, there are other factors that heretofore have been overlooked. The

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same criterion has not even been used, and few of the investigators have thought alike upon any one phase of the subject. However, with skilled workers and the minimum of variants, the investigations have been handicapped by the absence of fundamental viewpoints.

ALKALI TOLERANCE OF A PLANT BUT A MEASURE OF THE LIMIT OF ENDURANCE OF ITS ENZYMES

Many investigators of plant tolerance have used root elongation as a criterion, and there is a possibility in the use of such a criterion that most workers have failed to consider, and that is, in measuring the toxic limit of a plant for alkali, we are probably but measuring the limit of endurance of some of its growth enzymes. The amount of magnesium sulphate, for example, that will stop the root development of a plant, seems to be the amount of that salt that is required to kill the enzymes upon the root-tip, that are concerned with growth. Therefore, in dealing with alkali tolerance, when root elongation is used as a criterion, we are probably not dealing with the destruction of vegetative cells as much as we are with enzymes that affect their growth. This idea has been brought out by much investigation.

Kearney and Harter* in their work upon alkali tolerance, found that the age of the seeds of lupine had an important effect upon the limit of endurance of seedlings, when grown in pure salt solution. This difference was not noticeable when calcium was present in the culture solutions. it has the greatest amount of certain enzymic activity. This indicates will endure less alkali than will fresh seeds, and that light and temperature also affect the limit of endurance of plants. Plants will endure more alkali in the dark than they will in the light. The limit of endurance is also affected by the age of seedlings, the root-tip of a wheat plant seems to be most sensitive when 5 to 9 days old, this period being the time it has the greatest amount of certain enzymic activity. This indicates that, in alkali tolerance we are probably not dealing with the root-tip as vegetative tissue, as much as we are with the enzymes that affect its growth.

EXPERIMENTS WITH SEEDLINGS

In the work that will be reported, the elongation of the primary radicals was used as a criterion. The seedlings of the cereals were grown upon perforated aluminum discs that were floating in pans of tap water. Corn, citrus, and other seedlings were either sprouted between wet cloths or grown in sand beds, and when the primary radicals had

*The Comparative Tolerance of Various Plants for the Salts Common in Alkali Soils. U. S. D. A. Bureau of Plant Industry, Bull. 113, 1907.

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reached a length of about 2 cm. the seedlings were removed from the seedbed, their roots dipped into a thick magma of carbon black, and then placed under observation in the alkali solutions. The carbon formed little "black boots" about one-half cm. long over the end of each root. Any elongation of the roots then could be detected easily by a break in the black band just back of the rootcap.

TOXIC LIMITS OF CALCIUM HYDROXIDE AND SODIUM HYDROXIDE

As a result of many determinations, the limit of endurance of corn seedlings for calcium, when added as calcium hydroxide, was found to lie between 150 and 175 parts per million in solution, while the same corn seedlings will endure a concentration of twice that amount, or about 300 parts per million of sodium, as sodium hydroxide. This same phenomenon is true with cotton, wheat, and citrus seedlings and probably many other plants, that is, calcium hydroxide is much more toxic to them than is sodium hydroxide. The toxic limit of citrus seedlings, for example, is about 80 parts per million of calcium, as calcium hydroxide, and about 175 parts per million of sodium, as sodium hydroxide. Caustic soda is known to be much more destructive to organic matter than is calcium hydroxide. There is another reason underlying this phenomenon other than the effects of these bases upon growth enzymes, that will be discussed later.

RESISTANCE OF GROWTH ENZYMES TO SOLUTIONS OF SODIUM HYDROXIDE

The limit of endurance of wheat seedlings for sodium hydroxide, is about 250 parts per million. A solution slightly above this concentration, or sufficiently strong to stop all root elongation, was prepared, and six sets of wheat seedlings were placed in this solution. Set No. 1 was allowed to remain in the alkaline solution for 1 hour, set No. 2 was allowed to remain for 2 hours, set No. 3 for 3 hours, set No. 4 for 4 hours, set No. 5 for 5 hours, and set No. 6 for 24 hours. At the end of each period as indicated, the seedlings were taken from the alkaline solution, placed in tap water and allowed to remain overnight. In Table I are shown the results of the experiment.

It thus appears that wheat seedlings are able to remain in a toxic solution of sodium hydroxide for at least 2 hours, without any apparent injury. It required about five hours, under the conditions of the experiment, for the alkali to penetrate the root-tip and to destroy the enzymes that are associated with root elongation.

When toxic salts are added to seedling cultures in concentrations of the limit of endurance of the plant, the root-tips cease growing, but do

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not slough off. The vegetative cells do not seem to be ruptured. Usually another root system is developed that is able to withstand the concentration of alkali. The growth enzymes of some roots are more resistant than are those of other roots, even on the same plant.

This experiment indicates that it is probably the destruction of enzymes and not necessarily the destruction of vegetative tissue, that is most concerned in the alkali tolerance of plants.

TABLE I.—RESISTANCE OF ENZYMES TO SODIUM HYDROXIDE.

Number	Time in NaOH solution	Condition of roots after 18 hours in tap water
Control	0 hrs.	Good growth
1	1 hrs.	Good growth
2	2 hrs.	Good growth
3	3 hrs.	Slightly decreased growth
4	4 hrs.	Much decreased growth
5	5 hrs.	No growth
6	24 hrs.	No growth

ORDER OF TOXICITY OF ALKALI SALTS

From all the work that has been done on the limit of endurance of plants for alkali, regardless of what criterion has been used, there seems to be a fairly definite order of toxicitiy for all salts. The salts of the heavy metals, copper sulphate or mercuric chloride for example, are very toxic, and rank high in the table, while the salts of calcium, calcium sulphate or calcium nitrate, are not in ordinary concentrations toxic, and rank low in the table. The sodium salts are moderately toxic and so on. The salts that are common in alkaline soils, tend to arrange themselves in approximately the following order:

1. Magnesium sulphate
2. Magnesium chloride
3. Sodium carbonate
4. Sodium bicarbonate
5. Sodium chloride
6. Sodium sulphate
7. Calcium sulphate

The position of each salt in such a table of toxicity will probably vary with the plant used, and probably to a certain extent the order will vary with each investigator, but had we the methods of eliminating variants and of making our determinations accurately, no doubt a table of toxicity could be arranged that would be almost as definite as is Mendeleeff's table of atomic weights. This order of toxicity seems to have been gradually developed by the species through a long period of time, so that each salt now occupies its proper and definite place. In developing this order, the

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plant appears to have been directed by the same principles that have directed every other phase of its development. *Therefore, it looks as if the toxicity of any salt is determined by the units of time that the plant has come in contact with that salt during its long period of adaptation.*

Plants have come in contact with gypsum a great many times during this period, therefore, ordinary plants will tolerate a saturated solution of that salt. Plants have met with mercuric chloride and copper sulphate only upon rare occasions, and, therefore, these salts are extremely toxic. Most plants have come in contact with sodium chloride rather frequently, therefore, in the presence of calcium, they can endure a concentration of about one percent of that salt, and so the list might be added to indefinitely. It is probably possible to predict the frequency of the occurrence of a certain salt in the soil solution during the age of adaptation of a plant, if we know the limit of endurance of the plant for that particular salt; or knowing the frequency of the occurrence of a certain salt in the soil solution, we should be able to predict the degree of toxicity of that salt.

Calcium and magnesium are very much alike chemically, and it is reasonable to suppose that they should react similarly toward plants, but they do not. Magnesium sulphate is much more toxic than is calcium sulphate, and for the probable reason that the plant has met calcium sulphate 10 times during its period of adaptation, where it has met magnesium sulphate only once. Nearly all of the lower oxides, or "ous" salts, ferrous sulphate for example, are more toxic than are the higher oxides or "ic" salts—ferric sulphate. This is true probably because the "ous" salts exist in nature only in exceptional cases, as the oxygen of the air tends to oxidize every salt to its limit.

TOXIC ACTION OF CALCIUM HYDROXIDE AND SODIUM HYDROXIDE

Referring to the experiments with the relative toxicities of calcium hydroxide and sodium hydroxide, not one scientist in a hundred would guess that caustic lime is twice as toxic as is caustic soda, but if the hypothesis that the toxicity of a base, acid or salt, is dependent upon the number of times that the plant has come in contact with it, the results are exactly what one might expect. The ordinary calcium salts, calcium sulphate or calcium carbonate, are very abundant in nature, but caustic lime (calcium hydroxide) does not exist in appreciable amounts under ordinary circumstances. Caustic soda (sodium hydroxide) does exist, for when we drop phenolphthalein into a solution of sodium carbonate (black alkali) and get a red color, we get the reaction for sodium hydroxide, that is, for the OH ion. When sodium carbonate goes into solution in

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water, it is hydrolyzed with the formation of a certain amount of sodium hydroxide, so the plant, in becoming adapted to black alkali, also became adapted to sodium hydroxide. We might, therefore, expect the plant to be less affected by and more tolerant of sodium hydroxide than of calcium hydroxide, which is true.

AMMONIA AND ADAPTATION

Recently determinations were made of the limit of endurance of plants for ammonia gas dissolved in water, and a concentration of 40 parts per million was found sufficient to kill seedlings of corn and cotton. This is cited in order to show the possibility of predicting from the behavior of a plant, what the natural conditions must have been during its period of adaptation. The salts of ammonia, ammonium chloride or ammonium sulphate for example, are not very toxic, indicating that the plant has probably met with them frequently, but ammonia as a hydroxide is very toxic and ranks with the salts of some of the heavy metals. During the processes of nitrification and denitrification, and the formation of reduction products from nitrates and nitrites, some salts of ammonia could readily be evolved, but any intermediate products in the shape of a gas or of an hydroxide must have existed in extremely small amounts.

STIMULATION AND ADAPTATION

It is a well known fact that nearly all alkalies, even of the most toxic compounds, are stimulating to plants, when administered in small or proper amounts. This phenomenon is so general that hardly an exception can be recalled. If a certain salt, the base of which is some heavy metal, for example, is toxic in a concentration of 10 parts per million, it will quite likely be stimulating in a concentration of 1/10 part or less per million. The soil in which ordinary plants have become adapted to salts is such a heterogeneous mixture that hundreds of what are ordinarily considered as toxic compounds are likely to occur in it, although they may exist in extremely small amounts. The plant has become adapted to this condition, as is indicated when it is placed in a similar medium under artificial conditions. It requires what it has been accustomed to and it reacts favorably when given those things in culture media that occur in the normal soil solution. Most plants of economic importance have developed in humid areas, where we always find a certain amount of active organic matter in the soil solution. When such plants are transferred to arid regions where organic matter is usually lacking in the soil solution, ordinarily they do not thrive unless given a certain amount of organic matter. When given plenty of water, active organic matter seems often to be the limiting factor in arid and semi-arid agriculture, and apparently for the reasons just cited. The marked results that follow

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the application of manure or certain other forms of organic matter can scarcely be explained upon the basis of the plant food that they contain or upon their effect on the mechanical condition of the soil.

A plant appears to be able to become adapted to, and to establish a definite limit of endurance for a salt, without ever having come in contact with that salt in toxic concentrations. It must establish a toxic limit far in advance of the concentration of the alkali that is commonly met with, else the species would not have existed until now. There is probably a definite ratio between the concentration of a salt that is met with in daily growth, and its toxic limit. Furthermore, it seems possible for a plant to become adapted to a salt with which it has never come in contact, even in small amounts. Experience teaches that a plant may become adapted to one salt that is representative of a large class of salts.

MUTATIONS AND THE ORDER OF TOXICITY

It might also be suggested that a mutation may upset the order of toxicity, but this is seriously doubted. A mutation may cause a change with respect to the absolute amount of a salt that is required to prohibit growth, but there is only a slight possibility that the relative order of the salts will be changed. Calcium sulphate will probably remain at the bottom of the list, and magnesium sulphate in a position nearer the top. We should not expect calcium sulphate and magnesium sulphate to exchange places. Their relative positions seem fundamental and fixed.

There may be many apparent exceptions to this hypothesis, when it is considered in detail, but it is doubtful whether our present knowledge of the subject will justify us in calling those exceptions. It is possible that the individual plants under stress react differently from what they would do under ordinary conditions. This is true even in the behavior of chemical elements. Salts that lie close together in the table of toxicity, sodium chloride and sodium sulphate for example, may overlap one another, or under certain conditions, may even change places, but this must be included in our limit of error, which of necessity must be wide. Individual variation may play an important part, but these cases will probably be the exceptions and not the general rule. It certainly seems possible to arrange the great body of alkali salts in a table, in positions depending upon the units of time that the plant has come in contact with them during its period of adaptation.

IS THE TOXICITY DUE TO THE MOLECULE OR TO THE ION IN SOLUTION?

It is a matter of fairly common belief that the toxicity of an acid or a salt depends largely upon the amount of the positive ions present

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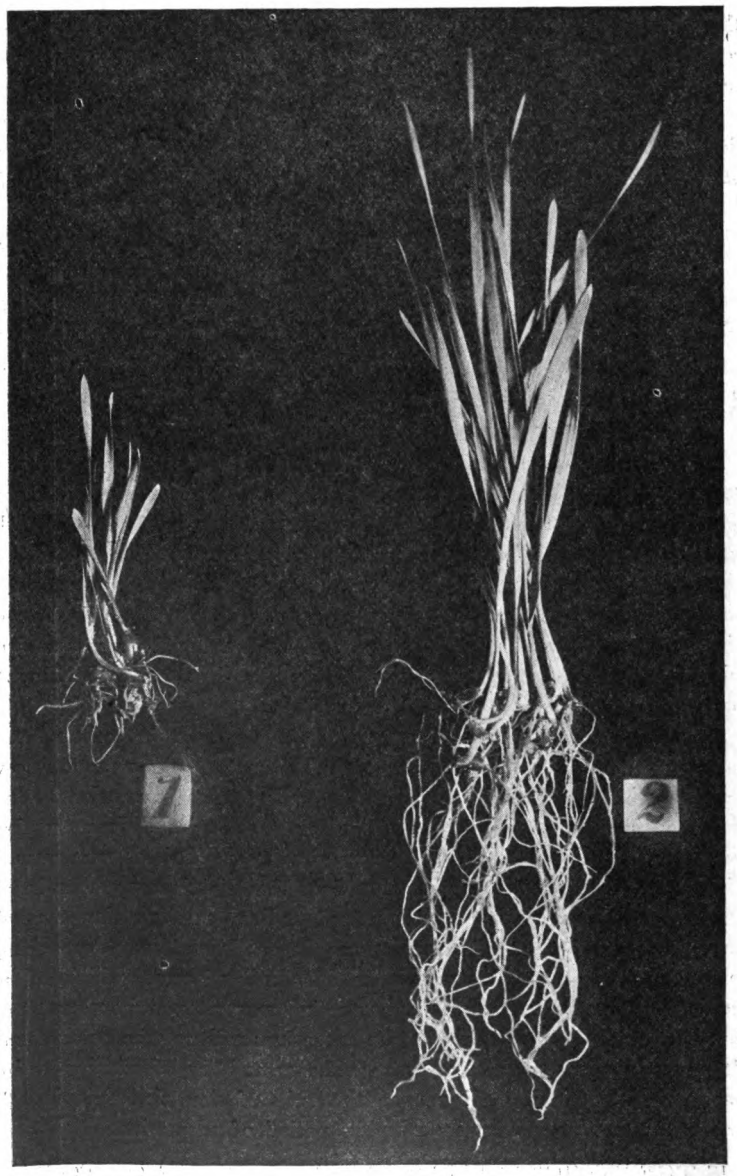

Fig. 1.—Wheat seedlings grown in pots of sand and watered exclusively with: (1) 4,000 parts per million sodium chloride; (2) 4,000 parts per million sodium chloride with 50 parts per million calcium oxide.

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in solution, that the toxicity of hydrochloric acid, for example, is largely a function of the H ion, while that of sodium sulphate may be attributed to the Na ion. This seems to be true in some cases, but there are so many exceptions to it that the hypothesis seems hardly tenable. Calcium hydroxide is very toxic, while plants can grow vigorously in a saturated solution of calcium sulphate. Sodium carbonate is toxic while sodium nitrate is not. Calcium hydroxide is more toxic than is sodium hydroxide, while calcium sulphate is much less toxic than sodium sulphate and the list could be added to almost indefinitely.

The degree of toxicity of a salt is not an accidental phenomenon, neither is it determined by physical or chemical laws. It is probably a biological phenomenon, and it has been established by the plant during its era of adaptation. Therefore, while in some cases, toxicity may depend upon the ion, in a great many other cases it seems to be due to the molecule rather than to the ion.

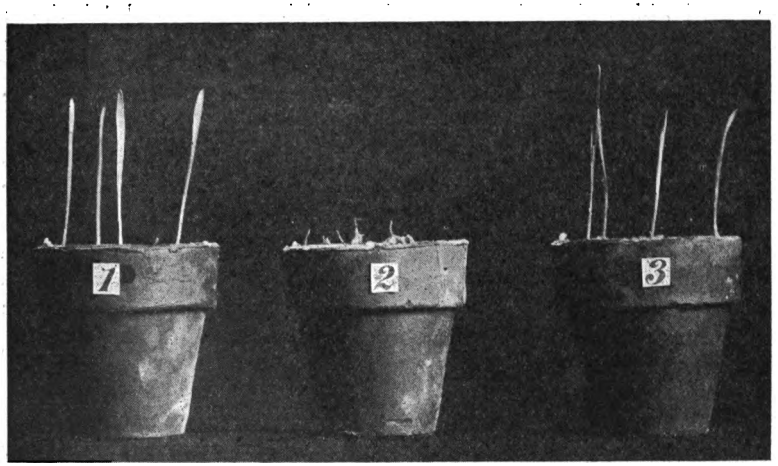

Fig. 2.—Wheat seedling grown in pots of pure aluminum hydroxide and watered exclusively with: (1) Distilled water; (2) 4,000 parts per million sodium chloride; (3) 4,000 parts per million sodium chloride with 50 parts per million calcium oxide.

THE AMELIORATING EFFECTS OF SMALL AMOUNTS OF CALCIUM

When cultures of wheat seedlings are grown in pure, distilled water, and pure sodium chloride is added to these cultures in increasing amounts, the plants will grow and their roots will elongate until a concentration of about 4,000 parts per million is reached, when the roots will cease to elongate. This is the "limit of endurance" for wheat in sodium chloride solutions. If, however, a small amount of a soluble calcium

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salt is added to the sodium chloride solutions the concentration of the sodium chloride may be increased to over 10,000 parts per million before the limit of endurance is reached. This phenomenon is more strikingly shown with some other plants than with wheat, although their limit of endurance of alkali may not be the same. This ameliorating effect of calcium in culture solutions is so well known that it needs no data and no comment. However, the fact that the phenomenon is true in certain other culture media is not so well known.

All soils contain enough calcium to mask this reaction, but with cultures growing in any medium that contains no calcium, such as quartz flour, pure sand, aluminum hydroxide, or carbon black, the same phenomenon is noticed. In figure 1 is shown the beneficial effects of calcium upon wheat seedlings that were grown in pure sand and watered with a solution of sodium chloride. In figure 2 is shown the effect of calcium upon cultures that were grown in aluminum hydroxide and watered with sodium chloride solution, and in figures 3 and 4 is shown the effect of calcium upon cultures that were grown in carbon black and watered with sodium chloride solution.

This ability of calcium to ameliorate or neutralize the toxic effect of alkali salts is one of the most interesting phenomena in plant physiology, and many explanations have been proposed. If alkali tolerance of plants is largely a phenomenon of adaptation, and if the degree of toxicity of any particular salt is determined by the units of time that the plant has come in contact with that salt during its age of adaptation, it appears that the ameliorating effect of calcium above referred to, may also be classified as a phenomenon of adaptation, and that immunity to alkali in the plant kingdom, and immunity to disease in the animal kingdom, are closely allied phenomena.

CALCIUM CARBONATE AND ALKALI TOLERANCE

In the arid and semi-arid regions of the West, where alkali is likely to occur, calcium carbonate is very prevalent. Hilgard says: "All arid soils are calcareous" and, barring extreme cases, he is probably correct. The solubility of calcium carbonate in pure water is only about 7 or 8 parts per million, this solubility, however, is increased by the presence of carbon dioxide. Bearing in mind the wide distribution of calcium carbonate and its low solubility, the plant, in becoming adapted to alkali, was almost sure to do this in the presence of calcium, even though it occurred in very small amounts. The amount of calcium in solution might have varied from a few parts per million in the case of calcium carbonate, to several thousand parts per million when gypsum or some other more soluble calcium salt occurred in the soil, but certainly some calcium was always present.

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Fig. 3.—Wheat seedlings grown in pots of carbon black and watered exclusively with: (1) Distilled water; (2) 1,000 parts per million sodium chloride; (3) 2,000 parts per million sodium chloride; (4) 3,000 parts per million sodium chloride; and (5) 4,000 parts per million sodium chloride.

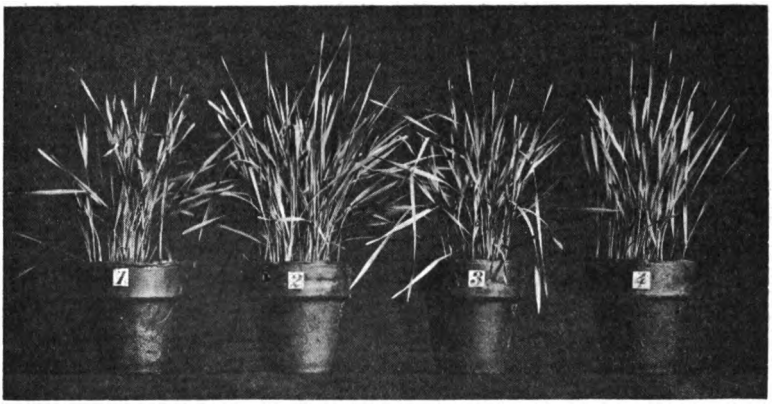

Fig. 4.—Wheat seedlings grown in pots of carbon black and watered exclusively with: (1) Distilled water; (2) 1,000 parts per million sodium chloride with 50 parts per million calcium oxide; (3) 2,000 parts per million sodium chloride with 50 parts per million calcium oxide; (4) 4,000 parts per million of sodium chloride with 50 parts per million calcium oxide.

Sodium chloride is probably the most common alkali salt that is met with in agricultural work. It has been shown* that when sodium chloride comes in contact with calcium carbonate, a reaction occurs with the formation of sodium carbonate, black alkali, and calcium chloride. This brings a calcium salt, calcium chloride, into solution, and we are now not dealing with the solubility of calcium carbonate, but with the more soluble calcium chloride. The plant in becoming adapted to sodium

*Breazeale, J. F. "Formation of Black Alkali in Calcareous Soils," Jour. Agr. Res. Vol. X, No. 11. 1917.

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chloride will do this in the presence of more or less calcium chloride. The maximum amount of calcium carbonate that can be dissolved by sodium chloride in the presence of carbon dioxide, under ordinary soil conditions, is only about 1,300 parts per million. When sodium sulphate occurs in the soil as an alkali it will bring not 1,300, but nearly 7,000 parts per million of calcium carbonate into solution. It will be seen then that the alkali, sodium sulphate, dissolves and makes available to plants, about five times as much calcium as does sodium chloride, and a plant in becoming adapted to sodium sulphate will be likely to come in contact with five times as much calcium as it will when becoming adapted to sodium chloride. We might, therefore, expect a plant affected with sodium sulphate poisoning to react more readily to an application of gypsum than one affected with sodium chloride poisoning. This was predicted from theoretical curves, and Kearney and Harter's work* indicates it.

The ameliorating effect of calcium, while very pronounced with both sodium chloride and sodium sulphate, is not nearly so marked in the case of sodium carbonate or black alkali, and the reason seems evident. In its age of adaptation, when the plant has encountered black alkali, there was necessarily very little calcium present in the solution. If gypsum or any soluble lime salt is added to a solution of sodium carbonate, or to a black alkali soil, a reaction will take place with the formation of calcium carbonate and sodium sulphate, and thus a greater part of the calcium will be removed from the solution. The black alkali soil can, therefore, contain but a very small amount of calcium in solution, and so the plant, when affected with black alkali poisoning, does not "anticipate" the presence of any appreciable amount of calcium, and consequently does not react to any great extent when given an application of calcium. However, as black alkali practically always occurs in the presence of calcium carbonate, there is always a very small amount of calcium in solution, so, theoretically, the plant should "anticipate" a little calcium and would react only a little when calcium appears in the cultures, and this is exactly what happens.

Magnesium, as magnesium sulphate or magnesium chloride, is another form of alkali that sometimes occurs in mixtures. Both of these salts act in very much the same way toward plants, so only one, magnesium sulphate, will be considered. Kearney and Harter found that the limit of endurance of lupine for magnesium sulphate is raised from 420 parts per million to 24,000 parts per million, or nearly 60 times, while the limit of endurance of alfalfa is raised over 300 times, by the presence of

*Loc. cit.

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gypsum. The interpretation of these phenomena seems to be that, in nature, the magnesium in the common minerals usually occurs associated with calcium, the calcium nearly always predominating, so, in becoming adapted to magnesium it is more than probable that the plant did so in the presence of a large excess of calcium, and, if poisoned by magnesium under artificial conditions, it would be likely to require conditions approaching those of its native habitat for successful growth.

ORDER OF TOXICITY OF ALKALI SALTS AS AFFECTED BY CALCIUM

In dealing with the ameliorating effect of calcium upon the common alkali salts it seems possible that the salts may be arranged in a definite order, the highest place in the list being occupied by the magnesium salts for the reason that they have been constantly associated with a large excess of calcium, and the lowest place in the list being occupied by sodium carbonate because it has been associated with very little soluble calcium. If enough data on the ameliorating effect of calcium upon the limit of endurance of plants for all alkali salts were available, the data could probably be arranged in the form of a table from which one might get a definite idea of the probable occurrence of calcium with these salts in the locality where the plant under consideration had become adapted.

Thus, it seems that the plant in past ages, in becoming adapted to alkali, always had a certain amount of calcium present, and now, when placed under stress, it requires a condition approaching that to which it is accustomed. This seems a natural and most reasonable way of looking at this phenomenon. The much discussed "physiologically balanced solution," is the solution that the plant has become adapted to during its ages of development.

IMMUNITY AND ADAPTATION

The Indians of the Great Southwest are very susceptible to tuberculosis, and this has been attributed to the fact that tuberculosis is a new disease among them, and that they have not yet developed an immunity to it. This seems to be true with other diseases than tuberculosis and with other races than Indians. The Hawaiians are fast being decimated by new diseases. On the other hand, the white race seems to be wearing out many such diseases, as measles and smallpox, by developing an immunity to them. This immunity may be conceived of as a definite chemical compound in the blood of the individual. Certain it is that immunity to disease is very pronounced in the animal kingdom, and it seems probable that it is but a phenomenon of adaptation.

To the plant, a salt such as sodium chloride, when accompanied by a little calcium, is an old disease and may be overcome, but sodium chloride without calcium is a new disease for which no immunity has been devel-

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oped. It is the opinion of the writer that alkali tolerance in plants depends largely upon immunity, which immunity is determined by the units of time that the plant has come in contact with the salt or mixtures of salts during its period of adaptation.

EXPERIMENTAL WORK WITH WHEAT SEEDLINGS

The writer has demonstrated repeatedly that, if wheat seedlings are first sprouted in distilled water and then placed in a 5,000-parts-per-million solution of sodium chloride, they will die. However, if the seedlings are first placed in a weak solution of calcium sulphate for a few days, then washed free from calcium and placed in the same 5,000-parts-per-million salt solution they will grow quite readily. There seems to be a "carry-over" effect from the time when calcium is present to a time when calcium is absent and when it is most needed. This suggested the following experiment:

Fifteen large enameled pans, each holding about 2,500 cc., were filled with solutions as described in Table II, and 500, or more, wheat seedlings were placed on perforated aluminum discs, each floating in one of these solutions. These solutions were then treated as described in Table II, and the cultures were kept under observation for 10 days. In order that the table may be more easily understood, the numbers were divided into five sets, A, B, C, D, and E.

TABLE II.—BEHAVIOR OF THE WHEAT SEEDLINGS WITH THE VARIOUS TREATMENTS NOTED.

No.	Treatment	Condition of plants after 10 days
	A	
1.	Plants grown in distilled water	Good
2.	Plants grown in 1 percent pure sodium chloride	Dying
3.	Plants grown in 1 percent pure sodium chloride together with 30 p.p.m., Ca, as calcium sulphate	Good
	These results indicate that a concentration of 1 percent of pure sodium chloride alone, is sufficient to kill seedling of wheat, but that if 30 p.p.m. of calcium is present in addition to the sodium chloride, the latter salt will not be toxic.	
	B	
4.	Plants grown in distilled water for 1 day and then transferred to 1 percent sodium chloride	Dying
5.	Plants grown in 30 p.p.m. Ca, as $CaSO_4$, for 1 day then transferred to 1 percent sodium chloride	Very poor
6.	Plants grown in distilled water for 1 day, then transferred to 1 percent sodium chloride with 30 p.p.m. Ca	Good
	It seems as if wheat seedlings, when grown for even 1 day in a solution of 30 p.p.m. of calcium will become slightly immune to sodium chloride poisoning.	
	C	
7.	Plants grown in distilled water for 2 days then in 1 percent sodium chloride	Dying
8.	Plants grown in 30 p.p.m. Ca for 2 days, then transferred to 1 percent sodium chloride	Poor

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9. Plants grown in distilled water for 2 days then in 1 percent sodium chloride with 30 p.p.m. Ca ..... Good

Wheat seedlings when grown for 2 days in a solution of 30 p.p.m. calcium, before being placed in a toxic solution of sodium chloride become partially immune to sodium chloride.

D

10. Plants grown in distilled water 4 days, then in 1 percent sodium chloride ..... Dying
11. Plants grown in 30 p.p.m. Ca for 4 days then in 1 percent sodium chloride ..... Fairly good
12. Plants grown in distilled water for 4 days then in 1 percent sodium chloride with 30 p.p.m. Ca ..... Good

Wheat seedling when grown for 4 days in a solution of 30 p.p.m. calcium become partially immune to sodium chloride.

E

13. Plants grown in distilled water for 6 days then in 1 percent sodium chloride ..... Dying
14. Plants grown in 30 p.p.m. Ca for 6 days, then in 1 percent sodium chloride ..... Good
15. Plants grown in distilled water for 6 days, then in 1 percent sodium chloride with 30 p.p.m. Ca ..... Good

It appears that wheat seedlings, when grown for 6 days in a solution of 30 p.p.m. calcium as calcium sulphate before being placed in a 1-percent solution of sodium chloride, become practically immune to sodium chloride poisoning at that concentration.

When running the foregoing culture solutions, every effort was made to eliminate completely traces of calcium from the cultures where it was supposed to be absent. When removing the cultures from the dilute calcium sulphate solutions before placing them in the toxic solutions of sodium chloride, the plants were washed thoroughly and allowed to stand in distilled water for 1 hour before being transferred. In this way there was no mechanical transfer of the calcium sulphate into the sodium chloride solutions. A few parts per million of calcium are sufficient to mask all results and it is no easy matter to eliminate all traces of this element. The culture pans, aluminum discs, and the wheat seeds were washed with dilute acid and then washed with distilled water before being used. Dust moves with air currents and is likely to settle in the culture pans; since these experiments were conducted in a locality where calcareous soils occur, the cultures were kept covered and protected from this source of error.

Briefly summing up the results of this and of duplicate experiments, it follows:

1. That wheat seedlings are killed by a concentration of 1 percent of pure sodium chloride when no calcium is present. See numbers 2, 4, 7, 10, and 13.

2. That seedlings will endure 1 percent of sodium chloride, provided a small amount of calcium is always present. See numbers 3, 6, 9, 12, and 15.

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3. That seedlings, if grown 1 or 2 days in a dilute solution of calcium, when transferred to a 1-percent solution of sodium chloride, while showing some immunity, will not withstand this concentration of salt. See numbers 5 and 6.

4. That seedlings, if first grown 4 or more days in a weak solution of calcium, will become practically immune to a 1-percent solution of sodium chloride. See numbers 11 and 14.

After 10 days observation, 100 seedlings were taken from each of the culture pans, washed, and analyzed for calcium. A few of these analyses are given in Table III.

TABLE III.—AMOUNT OF CALCIUM FOUND IN LOTS OF 100 WHEAT SEEDLINGS FROM THE VARIOUS CULTURE PANS.

No.	Treatment	Grams Ca in 100 plants
1.	Plants grown in distilled water	.0337
5.	Plants grown in 30 p.p.m. Ca, as $CaSO_4$, 1 day then in 1 percent sodium chloride	.0303
6.	Plants grown in distilled water 1 day, then in 1 percent sodium chloride with 30 p.p.m. Ca	.0340
14.	Plants grown in 30 p.p.m. Ca for 6 days, then in 1 percent sodium chloride	.0348

There seems hardly any evidence, from the results of these analyses, that the plants absorbed enough calcium from solutions 5, 6, and 14, to be detected. The original seeds, or the plants that were grown in distilled water, showed .0337 gram calcium. One of the other sets, No. 5, showed even a less amount, while the other two sets showed only slight increases over the control. Even the plants that were grown in cultures 14 and 15, (Table II), that gave such striking reactions to applications of calcium, showed little or no indications by their analyses that they had absorbed any calcium. It is reasonable to suppose that a plant grown for even a few days in a weak solution of gypsum, must necessarily absorb some calcium, but the amounts absorbed in the above experiment must have been exceedingly small, otherwise they would have been detected in the chemical analyses of the plants.

In work previously reported* it was shown that the presence of calcium did not hinder the absorption of sodium salts by the plant. Plants that were grown in solutions of sodium chloride and sodium sulphate, with small amounts of calcium present, absorbed as much, if not more, of the sodium salts than did plants that were grown in solutions of sodium salts that contained no calcium. The phenomenon is not due to the "damming-out" of the toxic salt. No satisfactory explanation has yet been

*"Effect of Lime Upon the Sodium Chloride Tolerance of Wheat Seedlings," J. A. LeClerc and J. F. Breazeale. Jour. Agr. Res. Vol. XVIII, No. 7. 1920.

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offered for the effect of small amounts of calcium upon the toxic properties of other salts.

When wheat seeds are placed in distilled water, preparatory to germination, some salts will exude from the seeds before the plumules and radicals appear. Potassium and phosphorus predominate in these exudations, but small amounts of calcium probably in organic combination, also come out. The writer has never observed that this exuded calcium has any effect in overcoming alkali poisoning. It seems as if calcium must be in an inorganic form in order to be able to ameliorate the toxic action of alkali. Anti-toxines must themselves be poisons, or else they would not be anti-toxines. A compound cannot be a food and at the same time an anti-toxine. It seems as if the inorganic and not the digested organic calcium is required by the plant when suffering from alkali poison.

SUMMARY

For many years the writer has been studying problems pertaining to alkali, both in its relation to practical agriculture and from a purely scientific standpoint, and the evidence is not wanting that the whole problem of alkali tolerance centers on a phenomenon of adaptation. It is true that such an hypothesis does not necessarily explain all the phenomena, but it does seem to bring the matter one step nearer the truth.

The fact that a wheat plant is killed by a solution of 1 part per million of copper, and that it will grow vigorously in a saturated solution of gypsum, is not an accidental phenomenon. The fact that a plant requires calcium even in minute quantities, when growing in the presence of an alkali, is not surprising. These facts are expressions of the conditions that the plant was subjected to during its age of adaptation. In all probability, if the plant had met copper sulphates frequently and in increasing amounts, and had never met gypsum during this age, the effect of these two salts would now be reversed—copper sulphate would be practically harmless, while gypsum would be toxic. If the plant had met pure sodium chloride instead of a mixture of sodium chloride and some lime salt, the pure salt would not now be so toxic. The plant in its native habitat was in a state that approached equilibrium with all the forces of nature, and had it not been in such a state it could not have continued to exist to this time. Every plant is but a product of environment, its likes and dislikes or its individualities were worked out ages ago and in the most reasonable way. The fundamentals are established and all in response to simple natural laws. The plant breeder may, therefore, modify certain superficial characters, for example the fruiting propensities of a plant, but the fundamental likes and dislikes yield slowly to the methods of the breeder.

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CONCLUSIONS

1. The limit of endurance of a plant for alkali salts seems to be determined by the amount of alkali that is required to kill the enzymes of the roots, that are concerned with growth.

2. There appears to be a definite order of toxicity of alkali salts, and the position of each salt in the order of toxicity depends upon the number of units of time that the plant has come in contact with the salt during its period of adaptation.

3. The presence of calcium, even in minute amounts, increases enormously the tolerance of wheat seedlings for sodium chloride and other alkalies.

4. Plants are able to utilize calcium at one period, and this calcium may be effective in overcoming alkali at a later period.

5. Plants may be inoculated, or "immmunized" against alkali, with calcium, just as readily as animals may be inoculated or vaccinated against certain diseases. Alkali tolerance in plants and immunity to disease in animals are closely allied phenomena, that is, they are both phenomena of adaptation.

6. A "physiologically balanced" solution may be defined as a solution that the plant became accustomed to during its era of adaptation.

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